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Quiet Supersonic Platform (QSP) Materials and Structures Focus Group Meeting, 26 June 2001

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I N S T I T U T E   F O R   D E F E N S E   A N A L Y S E S

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PREFACE

This document was prepared for the Defense Advanced Research Projects Agency in response to a task entitled “Quiet Supersonic Platform (QSP) Program Assessment.”

CONTENTS

I. INTRODUCTION

This document records presentations and discussions which took place at the Defense Advanced Research Projects Agency (DARPA) Focus Group meeting entitled "Materials and Structures Needs in the Quiet Supersonic Platform (QSP) Program," held at the Institute for Defense Analyses (IDA) on 26 June 2001. The purpose of this meeting, sponsored by DARPA's Dr. Richard Wlezien, was to discuss the current and emerging materials technologies and processes which might be applicable to meeting the structural and performance goals of the QSP Program. This program seeks to develop a supersonic aircraft that creates an initial shock pressure rise of only 0.3 lb/ft^2, achievable through a combination of shaping techniques and weight reduction, alleviating sonic boom effects and allowing for unrestricted supersonic flight over land.

The goal for this Focus Group meeting was to encourage interaction and dialogue among academic, commercial, and government representatives concerning possible materials and structures utilization within the QSP Program. Much of the group's discussion centered on newly developed materials and their potential structural applicability under the demanding flight conditions entailed by the goals set forth in the QSP Program.

The following written summary of these presentations and preliminary discussions give an overview of the concepts illustrated by the opening speakers. Readers are encouraged to look at the presentations for details regarding the technologies of interest.

After these initial presentations, the attendees were divided into three separate groups for more detailed discussions centering upon several questions posed by the meeting organizers. Charts enclosed in Appendix A of this document illustrate the summary outcome of these small-group deliberations. Appendix B contains the charts from the invited presentations given by various participants. The charts show various innovative materials and structures programs conceived and implemented by the participants' respective organizations and their colleagues.

Meeting attendees included government personnel active in the QSP Program, experts in the fields of materials and structures, and representatives from major aerospace companies. Appendix C is a list of attendees and their contact information.

We wish to thank the Focus Group participants for their insights and efforts and hope that this document will help DARPA to assess the possibility for the subsequent application of the diverse materials and structural concepts discussed at this meeting to the QSP Program, as well as set the stage for subsequent meetings relating to similar topics.

Rich Wlezien　　　　　　　　　　Lisa Veitch

II. DARPA QSP FOCUS GROUP MEETING ON MATERIALS AND STRUCTURES—SUMMARY

A. QSP PROGRAM OVERVIEW

Rich Wlezien from DARPA's Tactical Technology Office (TTO) began the focus group meeting by introducing the aims of the QSP Program. Those undertaking this 2-year program seek to study technologies which could be incorporated into an aircraft design meeting exceptional limits and goals for speed, weight, range, and boom generation. The challenging primary QSP requirement is producing an initial sonic boom shock strength of no more than 0.3 lb/ft^2. To fulfill this requirement, a vehicle will likely have thin wings (2 percent), be very long (high fineness ratio), and employ low-density structures. QSP system goals, after the initial sonic boom mitigation, include the following:

- 100,000-lb gross takeoff weight (GTOW)
- Cruise speed: Mach 2.4
- 6,000 nmi unrefueled range
- 20-percent payload weight fraction
- Stage 3 noise standards compliant.

Additional derived goals of the program consist of:

- Lift/drag ratio = 11
- Thrust specific fuel consumption = 1.05 lb/(lb-hr)
- Engine thrust/weight = 7.5
- 40-percent fuel weight fraction
- 40-percent empty structural weight fraction.

Dr. Wlezien commented that materials and structures represent an area of the QSP Program which has received very little attention thus far, and further emphasis is necessary to achieve such a low structural weight fraction and maintain safe high-speed flight. The aim of this program is not the development of radically new materials, but rather an integration of technologies that can be incorporated today. In addition, he

described the current program structure, which incorporates three branches: QSP technologies development undertaken by small companies and universities, airframe systems, and propulsion systems contractors. A coordinated effort is necessary to address goals such as the empty weight fraction, which in past supersonic aircraft has been considerably larger than 40 percent due primarily to engine sizing. The relatively infrequent opportunities that now seem to be available for design of new supersonic aircraft also complicate the job of incorporating past "lessons learned."

The Air Force has done studies that extrapolate today's technology, much of it gained from the National Aeronautics and Space Administration (NASA) High Speed Research (HSR) program, to design a notional Mach 2.4, 32,000 lb payload Future Strike Aircraft with a range of 6,000 nmi. Its 427,000-lb GTOW, however, makes it an expensive vehicle that would be difficult to market to a potential user. The QSP Program, therefore, seeks to lower GTOW to 100,000 lb, while maintaining a 20,000-lb payload. At the time of this meeting, the program was halfway through the first year of its 2-year duration. DARPA will soon solicit the airframe companies for proposals for the second year of the program in order to help put together a more comprehensive effort.

Last, Dr. Wlezien discussed the advantages of foamed metallic structures in aircraft manufacturing. These advantages include their potential for cost-effective fabrication and their utility, both structurally and functionally, as an aid to laminar flow and thermal dissipation.

B. DARPA MULTIFUNCTIONAL SYNTHETIC MATERIALS PROGRAM

Leo Christodoulou of DARPA's Defense Sciences Office (DSO) spoke concerning new materials systems and synthetic multifunctional materials (SMFM) which could potentially reduce parasitic aircraft structural weight. Ideally, the entire aircraft structure would either serve additional functions or be eliminated. Relevant DSO structural concepts include

- Power structures
- Actuating and sensing structures
- Survivable structures
- Autogenous (self-healing) structures
- Autophagous (self-consuming) structures
- Thermal control structures.

Structural Amorphous Materials (SAM), another materials class that Dr. Christodoulou discussed, presents no long-range order or grain boundaries. These "metallic glasses" can be cast in large pieces, like conventional metals. As these substances deform, more of the material participates in the deformation process (hence processes such as shear band localization are prevented), creating dynamic toughness as the structure is loaded.

Dr. Christodoulou next explained the Accelerated Insertion of Materials (AIM) Initiative, intended to increase the speed of material insertion into new systems and to reduce the cost and risk of doing so. To promote use of state-of-the-art materials, AIM would organize existing materials knowledge into a Web-based system. Through this knowledge base, designers could acquire all the information that they would need to make a materials choice for their particular project. Dr. Christodoulou suggested in conclusion that although he had discussed some concepts that are far from actual implementation, this Web-based materials system is closer to becoming a reality for use by designers.

C. AIR FORCE RESEARCH LABORATORY PROGRAMS— MATERIALS AND MANUFACTURING DIRECTORATE

Representing the Air Force Research Laboratory (AFRL) Materials and Manufacturing Directorate, Edward Hermes presented an overview of the current Air Force Materials and Manufacturing Technology, which would have relevance for the supersonic flight arena. The specific technologies of interest for structural and propulsion systems include the following:

- High-temperature poly matrix composites (PMCs)
- Carbon-carbon materials
- Thermal management materials
- High-fidelity analysis tools
- Processing for dimensional control
- Integrated High-Performance Turbine Engine Technology (IHPTET)
- Life prediction/high-cycle fatigue.

Dr. Hermes additionally pointed to current AFRL programs affecting structures and propulsion, such as:

- Composites affordability initiative
- Metals affordability initiative

- Forging supplier initiative
- Casting supplier initiative
- Laser shock peening
- Engine rotor life extension.

Last, Dr. Hermes identified issues that prevent the utilization of innovative materials, namely lack of confidence in materials models and affordability and access barriers.

D. AFRL—AIR VEHICLES DIRECTORATE

Dr. David Pratt from the Structures Division of the AFRL's Air Vehicles Directorate discussed QSP issues from a structural perspective. He defined the main structural issues to be:

- Embedded engine and aft decks
- Lightweight structures
- Design/analysis—probabilistic methods
- Aeroelasticity
- Mission-adaptable structures.

Dr. Pratt discussed various programs underway that were applicable to the above-listed categories:

- Ceramic exhaust-washed thermal structures
- Combined acoustic and thermal testing facilities
- Advanced Lightweight Affordable Fuselage Structures (ALAFS) Program
- Composites Affordability Initiative
- Ultra-lightweight structures program.

Dr. Pratt commented on the possibility of utilizing Active Aeroelastic Wings (AAW); High L/D Active (HiLDA) Wings; and additional adaptive structures, such as leading edges and inlets, as possible means to fulfill the QSP goals. At this point, he introduced Maj. Brian Sanders to speak further about adaptive structures designs.

Maj. Sanders briefly identified three adaptive structures concepts of interest. The first, the Smart Wing Program, has been demonstrated with actual componentry at Mach 0.8. Second, the Smart Aircraft and Marine ProjectS demonstratiON (SAMPSON) program, most useful at supersonic speeds, would use shape-memory alloys to modify

flow in an inlet. Third, energy harvesting is a concept in which thermal energy from the aircraft skin would be exploited to drive actuation systems.

E. STRUCTURES AND MATERIALS TECHNOLOGIES FOR HIGH-SPEED FLIGHT VEHICLES

Dennis Dicus and Michael Nemeth of NASA's Langley Research Center gave an overview of some of the technologies stemming from the HSR Program, as well as current NASA research projects which are useful for high-speed flight. The key issue regarding airframe materials technology during the HSR Program was the lack of a long-term, high-temperature materials database for High-Speed Civil Transport (HSCT) airframes. In particular, the increase of cruise speeds from Mach 2.0 to 2.4 introduces significant additional challenges and issues for structural materials.

Technologies resulting from the HSR Program that are still under consideration for high-speed aircraft include lightweight wing and fuselage structures with variable stiffness distributions and the use of composite materials made from the PETI-5 polymer system. Beyond HSR Program research, NASA has looked at the Vacuum-Assisted Resin Transfer Molding (VARTM) Process, potentially a low-cost process because there is no need for an autoclave, and metal/polymer matrix composite hybrid materials, which offer improved fatigue life and in-plane damping. In addition, advanced aluminum alloys offer strength-toughness advantages necessary for Mach 2 flying conditions. Friction stir-welded joints improve on traditional riveted joints in the areas of weight, cost, and performance. Other materials and structure concepts that NASA has considered and which might be used in high-speed flight projects include Al-Mg-Sc alloys; new titanium alloys; titanium honeycombs, four-sheet sandwiches, and truss-core sandwiches.

F. 3-D CELLULAR METALS

Haydn Wadley of the University of Virginia illustrated the possibilities offered by three-dimensional (3–D) cellular metals, an area of rapid growth over the last 10 years. These cellular metals can be divided into two subcategories, stochastic materials, such as metal foams, and periodic metals, encompassing prismatic materials and lattice or truss structures. Metal lattices, with densities spanning 1–10 percent of the original solid metal, are a material form of interest to the aircraft industry. Truss structures allow for design to specifications and placement of the trusses in ways that achieve optimized geometries. Cellular metals are manufactured in various ways, such as templated or foaming solidification (liquid), metal fabric layup (solid), and templated condensation (vapor).

Dr. Wadley continued by discussing specific types of cellular metal structures, which can be formed in a variety of size scales. Woven metal microtubes offer efficient heat-transfer capability. An inexpensive approach to creating lattice structures uses tubes woven into metal sheets, which are then stacked, sprayed with a transient liquid-phase sintering/bonding agent, and heated. The result is a strong but flexible truss structure. Constructed cellular metals are a revolutionary and inexpensive means of creating trusses simply by pressing alternating nodes from a perforated metal sheet. Dr. Wadley's charts show different truss geometries, fabrication approaches and properties of structures fabricated from them.

G. DESIGNING WITH MATERIALS

Tony Evans from Princeton University began by explaining the properties of metal foams and truss structures. Although inexpensive, metal foams have limited stiffness and strength, and periodic structures may be a better choice under loaded conditions. Optimized truss structures allow for pure tensile and compressive stresses, with no bending. In addition, the openings in the trusses allow for fluid flow to aid thermal management. Under bending conditions, trusses perform much better than foams and nearly as well as honeycomb structures; under compressive loads, trusses perform similarly to traditional heat-stiffened structures.

Trusses also hold possibilities as curved panels because of their light weight and as heat exchangers, by using a metal with high thermal conductivity to draw heat into the lattice, where it can easily transfer to a fluid flowing through the core.

Dr. Evans showed a brief movie demonstrating that when a 45-deg weaving technology was utilized to create a truss structure, the core material did not undergo shape deformation under bending loads; the failure mechanism was instead the plastic bending of the face sheet.

H. DISCUSSION

Following the above-summarized presentations, the participants were divided into three groups for discussion of the following six questions:

1. How would a Mach number range (2.0–2.4) affect new requirements?
2. How would these materials and designs be demonstrated, and what would be the maturity level required to do this?
3. How would design practices need to change if current materials are used?

4. What are the manufacturing issues?
5. What are the aeroelasticity issues for this type of vehicle?
6. What is needed to do a probabilistic design criteria approach?

The resulting comments from the three groups are summarized in this document in Appendix A.

Following the outbriefings from the groups, Dr. Wlezien thanked the participants for the day's open discussion. He summarized the three major themes he felt had emerged from the small-group deliberations:

- The materials and structures issues appear to be more of an engineering problem than a science problem. Multifunctional concepts present a potentially large payoff for QSP-type applications.
- Mach 2.2 presents a critical, if somewhat blurry, juncture in materials selection. Mach 2.4 may still be preferred for military needs.
- A need for engineering materials data exists, but QSP can still pursue avenues such as scaling up materials and testing and utilizing probabilistic design methods.

Dr. Wlezien then asked for a report card from the group detailing the responses of the attendees to the day's activities. Furthermore, he stated that he had found the Focus Group to be valuable, and he would be willing to sponsor an additional meeting. Finally, he explained that he had purposefully not defined a specific outcome for this meeting in the hopes that the discussion process in the areas of materials and structures would be iterative, with potential for further focus at a subsequent modeling and simulation (M&S) meeting.

GLOSSARY

AAW	active aeroelastic wing
AFRL	Air Force Research Laboratory
AIM	accelerated insertion of materials
ALAFS	Advanced Lightweight Affordable Fuselage Structures Program
DARPA	Defense Advanced Research Projects Agency
DSO	Defense Sciences Office
GTOW	gross takeoff weight
HiLDA	High L/D Active
HSCT	High-Speed Civil Transport
HSR	High-Speed Research Program
IDA	Institute for Defense Analyses
IHPTET	Integrated High-Performance Turbine Engine Technology
M&S	modeling and simulation
NASA	National Aeronautics and Space Administration
PMC	poly matrix composites
QSP	Quiet Supersonic Platform Program
SAM	structural amorphous materials
SAMPSON	Smart Aircraft and Marine ProjectS DemonstratiON Program
SMFM	synthetic multifunctional materials
TTO	Tactical Technology Office
VARTM	Vacuum-Assisted Resin Transfer Molding

APPENDIX A

SUMMARY CHARTS FROM DISCUSSION GROUPS

GROUP I DISCUSSION SUMMARY

- QSP weight goal not achievable through airframe weight reduction alone
  - Much potential for weight reduction in systems
  - Need to identify and prioritize
  - Current systems generally driven by cost (COTS)
  - Multi use structures offer potential to integrate structure and systems weight

- Much weight (and cost) reduction potential in unitization and joining
  - Develop required design techniques
- Hybrid structure
  - Tailor materials and structural concepts to specific areas of structure
  - Truss core structure for high stiffness
  - Amorphous material for high strength and fracture toughness

- Interesting materials and structural concepts
  - Tycor
  - GLARE
  - Al-Li
- Probabilistic Design
  - Need to understand loads, fly behavior to avoid conservative design

- Foam material
  - G-1 level
  - Repeatability of properties
- Sandwich Construction
  - Industry having terrible time integrating
  - High speed machining
- AIM
  - Accelerated Insertion of Materials

- Structural weight
  - Small fraction of MTOW
- "Low hanging fruit" in other areas
  - Manufacturing
    - Reduced Part Count
  - Systems
    - Electric
    - Hydraulic
    - Environmental

    Integrated Multipurpose Distributed Systems

    Compact Hybrid Actuation --DARPA Program
  - Landing Gear
    - Don't go there

- System reliability
- System access

  Can translate to weight
- Bonded structure
  - Process intensive
  - Inspection
  - Surface preparation
- Design process
- Integration of full use of available technology
- Multifunctional structural components

- Amorphous metals
  - Fine grain structure
  - Strength, toughness
  - Perfect processing to get perfect microstructure
- Hybrid construction
- Aluminum lithium
  - Newer alloys
- Monolithic structure
  - Larger, fewer parts
  - Aircraft component level

GROUP II DISCUSSION SUMMARY

- Materials readiness
  - Time for demo--flight vs. ground
  - Time for application
- Flutter/aeroelastic ➡ must fly
  - Other ➡ ground
- Drivers
  - Weight
  - Thermal load vs. temperature
  - Fatigue/durability/design life
  - Creep
  - Thermal management
  - Damage tolerance
  - Dissimilar joining
  - Processing
    - Forming, tolerances, design criteria, $

Mach?

- Civilian $\Rightarrow$ little impact to go faster
- M=2.0 $\Rightarrow$ more materials options, lower risk
- Military $\Rightarrow$ go faster until cost too much
- Composites $\Rightarrow$ M 2.2 (better stiffness)
- Metallic sandwich $\Rightarrow$ 2.4+ active cool?
- Titanium $\Rightarrow$ M=2.7, but too heavy?

Demo Approach

- TRL = 6?
  - Ground
    - Scale build up approach
    - Thermal, mechanical load cycling
    - Full scale component
  - Need AIM to reduce cost!!!
    - Proof/validation needed
  - Aeroelastic
    - Wind tunnel + fly
    - All flight conditions
- QSP
  - Design/sizing tools don't capture new structures concepts
    - Need FEM analysis
  - Invest in design/analysis processes to accelerate transition
    - "Relative Answer"
    - "Don't converge too quickly"

Demo Approach (Cont'd)

  - Scaling laws/linkages (more global issue—bigger than QSP)
  - Revise V&V process
    - Scale build up approach
- QSP scale-up panel size
  - High fidelity instruments
  - Combined environment
- NDE/quality control
  - Design consideration
- Failure criteria
  - Convince industry first
  - Monte Carlo on components
  - Define acceptable failure rate

Summary

- Discussed design drivers
- Mach trade
  - Benefit of higher speed not substantial for civilian
  - Composites good to Mach 2.2 (superior stiffness)
  - Metallics for M=2.2 - 2.7+
    - Active cooling?
- TRL = 6 – requires full scale ground test for combined loads
  - Aeroelasticity must fly
- Must have AIM to reduce cost
- Need to develop design/analysis tools
  - Look for relative answers
  - Avoid convergence too quickly

Summary (Cont'd)

- Develop scaling laws, V&V process
- Probabilistic failure criteria
  - Convince industry first

QSP Recommendation

- Scale up testing of candidate materials/structures concepts
  - Combined environment
  - High fidelity instrumentation
- Develop design methods
- Subscale assembly/joining test
- Update design requirements and/or practices to take advantage of new M&S and processes

GROUP III DISCUSSION SUMMARY

Wing-Main

- Conductive
- Low CTE
- High strength, moderate stiffness
- Thermal flexibility
- Attachment of load-bearing surface with sub-structure
- Lightweight material that achieves high temperature fast

Thin Wing

- Structured cellular
  - Robust to small damage (sensitivity)
- Need data in normal engineering formats
- Repair of structure?
- How manufactured?
- Unit loading to reser.?
  - Size panels
- Assembly!
- Active cooling?
  - Selective possibly
  - Basic structure—not likely
  - Some lamination flow benefit
- Adaptive Structure?
  - Yes—payoffs?

Thin Wing (Cont'd)

- Free-form processing
  - Not thin wing weight competitive
  - Possibly cost issue
- Need high stiffness/weight ratio
- VARTM processing PETI-5
- Large unitized structure without fasteners
- Composite—best
- Be-Al-Mg alloys?

Periodic Sandwich

- Tailored internal topology
  - Open cell—no corrosion
  - Cheap manufacturing (to honeycomb)
  - Material flexibility
  - Multifunctional
    - Thermal management
    - Adaptive structure
  - Damping/noise suppression (flutter/acoustic)
  - Damage containment
  - Controllable isotropy

Multifunctional Structures

- Antennas
- Subsystems
  - Power/Batteries
  - Controls
  - ECS
  - Thermal management
  - Fuel
  - IVHM

Periodic Sandwich or EEDS Sandwich?

- Compare to honeycomb
  - What compare “standard” or optimized.
- General Answers
  - Joining concepts, etc.
- “ilities”

Probabilistic Methods

- Tools
- Events
- Materials = need lots more materials data

Summary of Benefits

- Reduced Factor-of-Safety (1-2% GTOW)
- Multifunctional Structures (1-2%)
- Unitized Composites (4-5%)
- Improved MDO Structures/Materials (2-3%)
- Gust Load Alleviation (?)
- Probabilistic Design (5%)
- Tailored Anisotropy (1-2%)
- Build Innovative Structures and Test to Failure

APPENDIX B

PRESENTATION CHARTS

Structural Materials and Devices

L. Christodoulou
DARPA/DSO

B-1

Scope of Activities

1. New Material Systems
   a) Ultralight materials
   b) Synthetic Multifunctional Materials
      i. Stochastic
      ii. Periodic
   c) Structural Amorphous Metals
2. Accelerated Introduction of Materials
3. Prognosis (Capability Prediction)

B-2

Synthetic Multifunctional Materials: *Structure* +…

Agents: A. Crowson (ARO), S. Fishman (ONR)

Structural Amorphous Metals

Agents: D. Hardwick (AFRL), G. Yoder & W. Messick (ONR), and W. Mullins (ARO) and R. Dowding (ARL)

B-3

Synthetic Multifunctional Materials (SMFM)

Grand Challenge:

Create application-specific material systems with optimized functions by design.

Synthetic Multifunctional Materials

B-5

Problem:

"Structure" is Parasitic to the mission –

It provides a platform for payload, sensor communications, etc.

Solution:

- **Eliminate**
- **Give structure other functions!!**

Structure +…

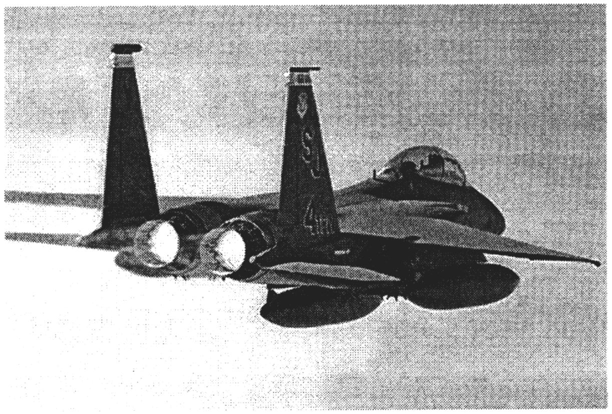
The Problem

DARPA

Fact: <u>Structure</u> constitutes a large fraction of total system weight

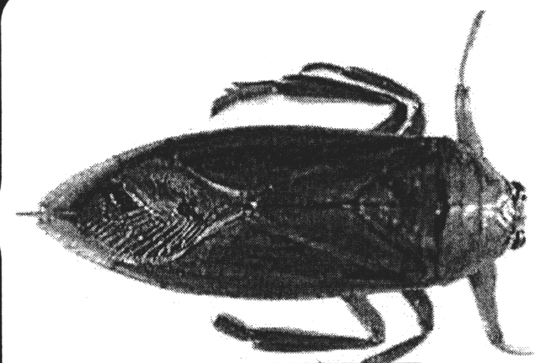
System	Total (lb.)	Structure (lb.)	Struct. Fract.	Payload (lb.)	Payload Fract.
Sender	10	5	50%	2	20%
F-18E/F	66,000	34,900	53%	13,700	21%
747-400	800,000	384,500	48%	285,000	36%
Satellite			19%		34%
Microstar (goals)	86 gms.	22.5 gms.	26%	18 gms.	21%

Synthetic Multifunctional Materials: Program Vision



System Components

- Load-bearing structure
- Propulsion
- Power (fuel)
- Payload



Artificial systems

- Functions designed in isolation
- Components have a *single* function

Nature's systems

- Functions evolved in unison
- Components are *multi*functional

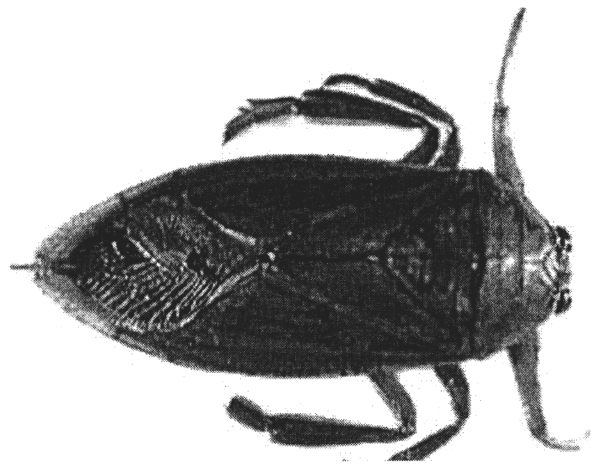
Program aims to change the way structures are designed, built and used.

Natural Multifunctional Material: An Example

<u>*Cuticle*</u>

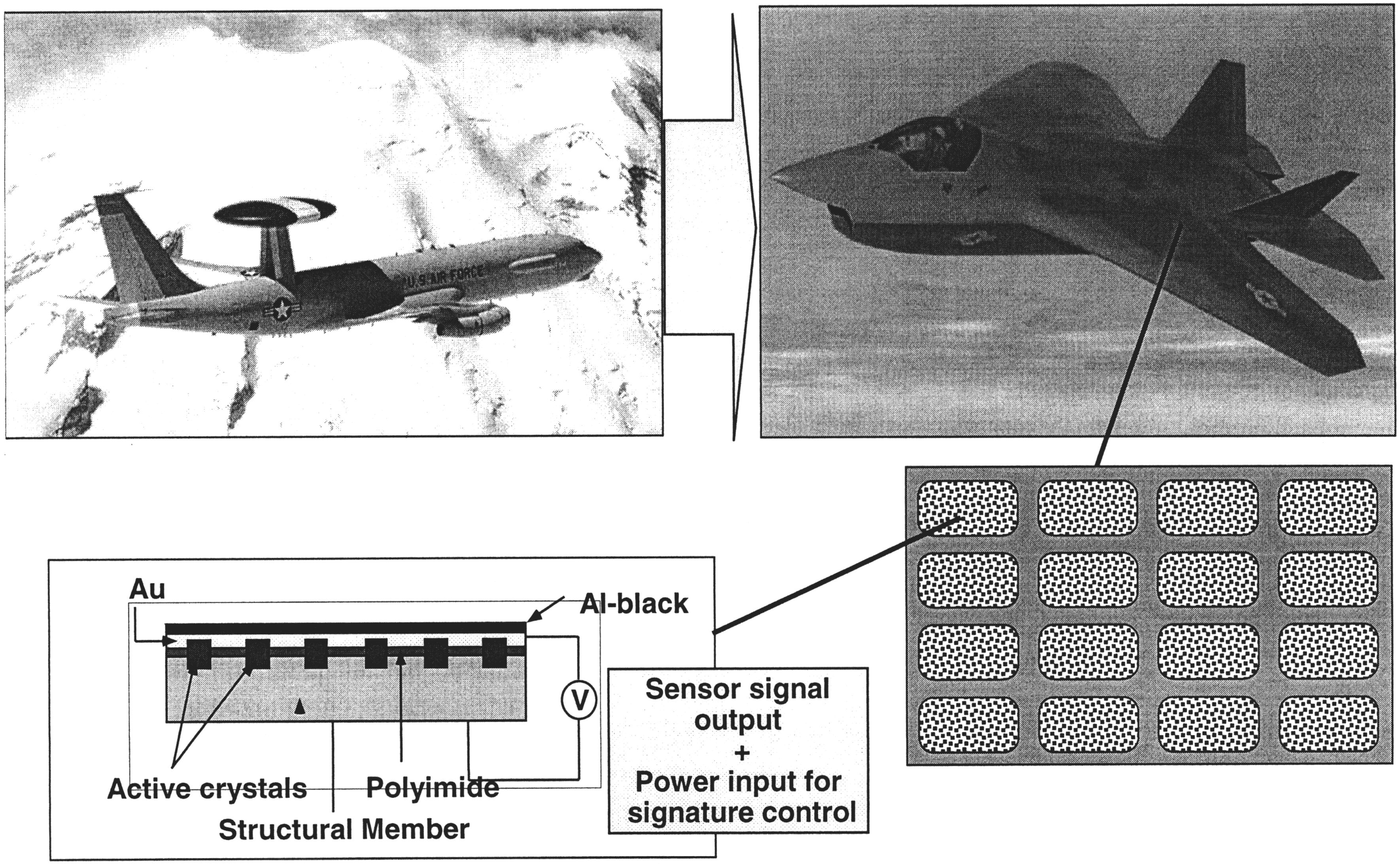
A Hetero-nanostructured Material:
(Compositional & Morphological)

Chitin fiber (3 nm x 180 nm -- like glass fibers)
orientation
volume fraction
Protein matrix
pH control
water content control
modulus control
Pore canals
connection between epidermal cells and cuticle for communication and repair
Interlined holes
filled with resilin
campaniform sensilla
Multi-layered arrangement
stiffer outer/softer inner layer



Design issues solved by Nature!
- Fiber orientation/placement
- Fiber matrix interaction based on chemical control of interfaces
- **Holes/canals distribution without weakening structure**
- **Self-repair, growth**
- **Thermal management**

Multifunctional Transformation



B-9

Specific Objectives

- To discover the physical bases for the evolution of functions (structural, electromagnetic, thermal, etc).
- To understand and be able to select for desired properties at the salient scale.
- To establish the capability for reliable prediction of function by models, rules and design tools.

13-10

- To elucidate the hierarchical organization that gives rise to macroscopically apparent functions
- To develop 'fast' techniques for optimization for multifunctionality.

  ➢Create and demonstrate application-specific material systems with multiple optimized functions by design.

  ➢Establish approaches and design tools for synthesis, fabrication and use.

  ➢Enable seamless integration with the (existing or evolving) component/subsystem/system design tools

SMFM - Challenges

- **How do we optimize functions in a multifunctional material?**
- **How do we capture the features that control the functions of a particular material system?**
  - **Data base population. (Dominance of the extremes).**
  - **Coupled dependence of properties on structural features.**
  - **Evolution of "anomalous" microstructure.**
- **What mathematical techniques are available or need to be developed to enable "multifunctionality" by design?**
  - **Reducing complexity.**
  - **Incorporating variability in design. (Stochastic optimization in design).**

Synthetic Multifunctional Materials:
Development of SMFM Design Methodologies

B-12

Materials Characteristics	
Mechanical	Stress - Strain
Thermal	Heat Flux - Temp. Gradient
Electric	Flux Density - Field Intensity
Magnetic	Flux Density - Field Intensity
Ballistic	Energy Density-HSR response
Repair	????

Research Issues

Multi-phase multi-component geometric arrangements

Transition from micro to macro scales

Competing linear and nonlinear responses

Anisotropic behavior

Discreet vs. continuous properties

Major Challenge: Integration of diverse features/requirements into useful materials and design tools

SMFM Program Elements

1. **Power Structures**
   a. Power Fibers
   b. Power laminates
   c. Structure-integrated fuel cells
   d. Charge/hydrogen storage structures
2. **Actuating and sensing structures**
3. **Survivable structures**
4. **Autogenous (Self healing) structures**
5. **Autophagous (Self consuming) structures**
6. **Thermal control structures – transition**

Models, Rules and Tools

Specific Demonstrations

B-13

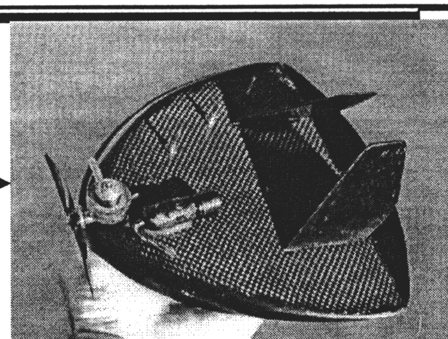
SMFM Power Structures

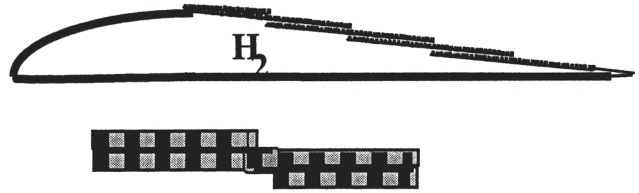
[redacted]

13-14

- Power Structures
- Sens./Comm. Structures
- Self Actuating Structures
- Self healing/Decon.
- Survivable Structures
- Autophagous Structures

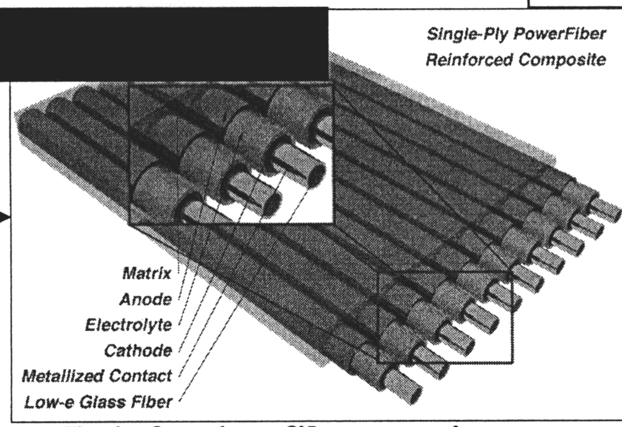
Models, Rules & Tools





Metal element serving as wing structure, antenna and current collector

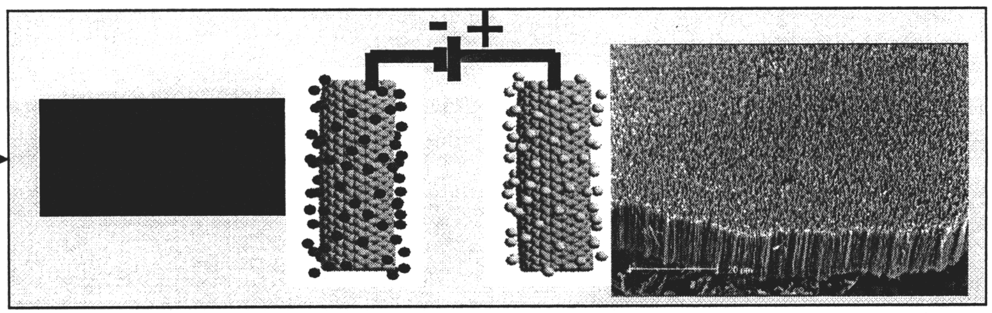
[redacted]



Reinforcing fiber serving as structure and battery

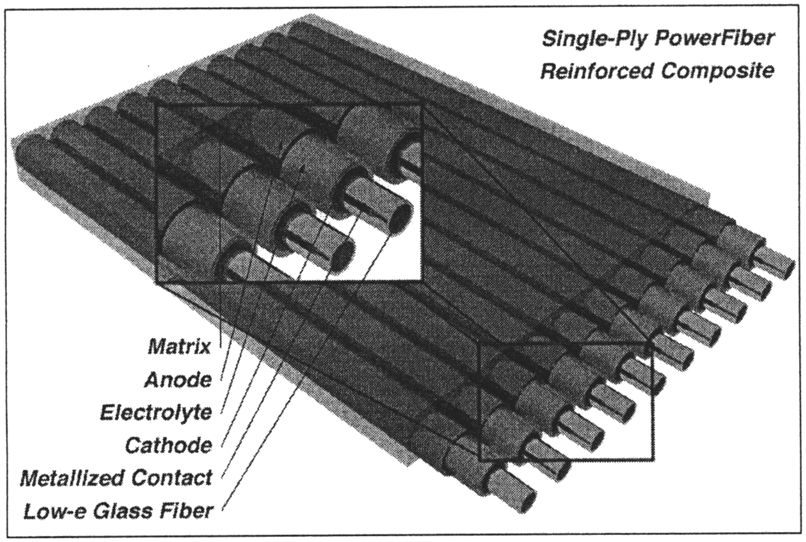
- Localized power source(s)
- Integral antennas and actuators
- Distributed power for damage tolerance and low transmission loss

[redacted]



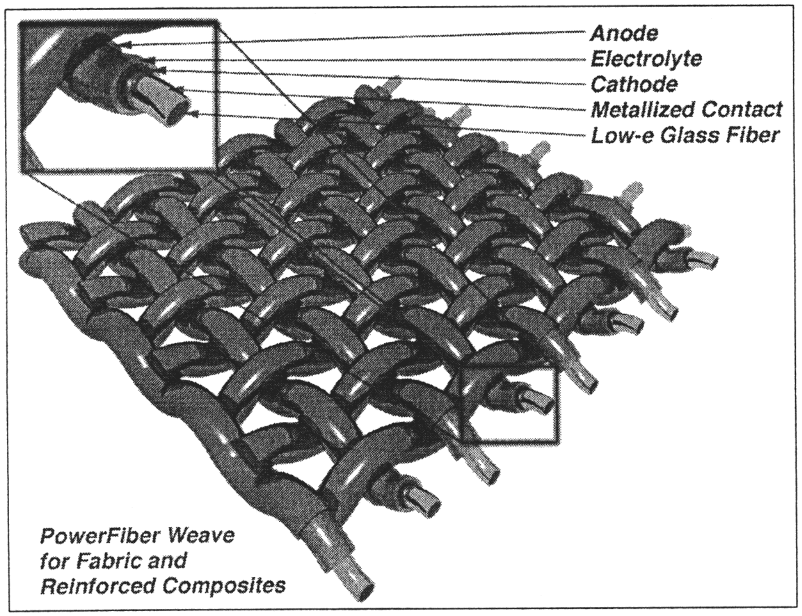
CNT serving as structure, actuator, and supercapacitor

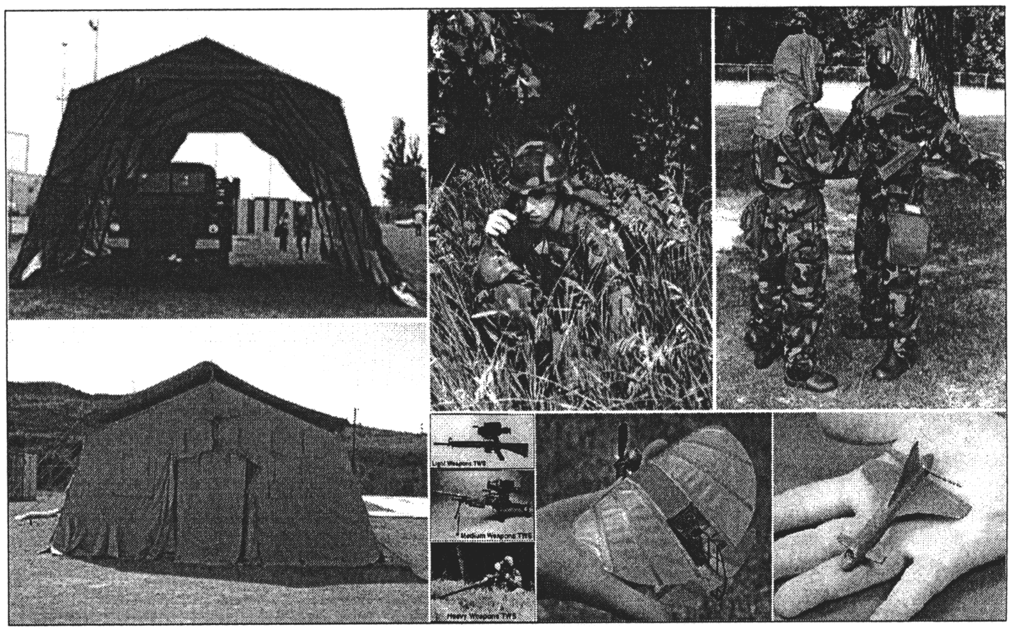
SMFM Power Fibers



Integrate power with structure

- **Robust energy source**
- **Non parasitic**
- **Transparent to user**

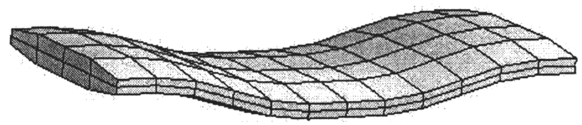




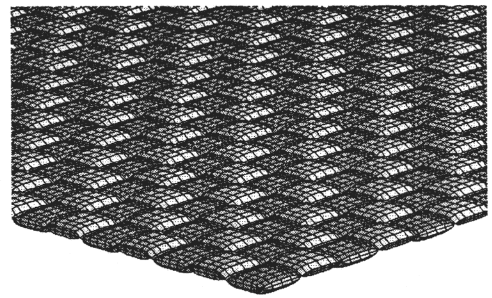
B-15

SMFM Power Fibers

- Production of novel woven zylon/lithium ion battery fabrics with dual functionalities.
- Development of computational models and tools for desi
of woven fabrics and structures.

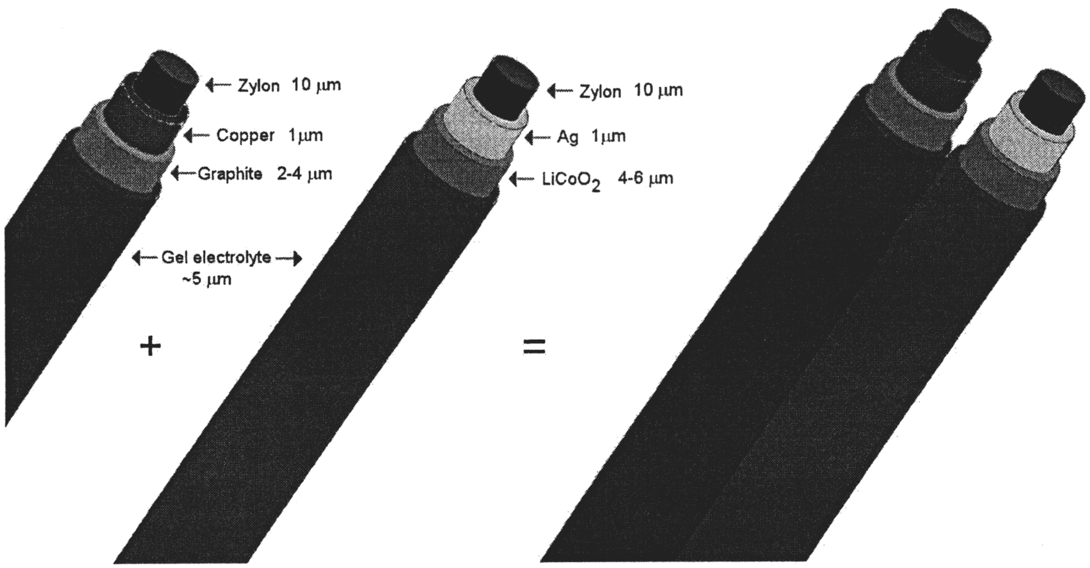


Detailed Yarn Model

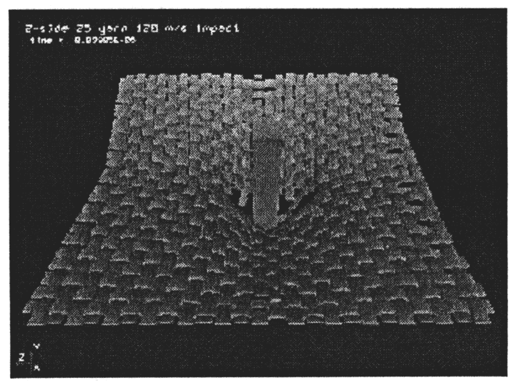


Detailed Woven Fabric Model

B-16

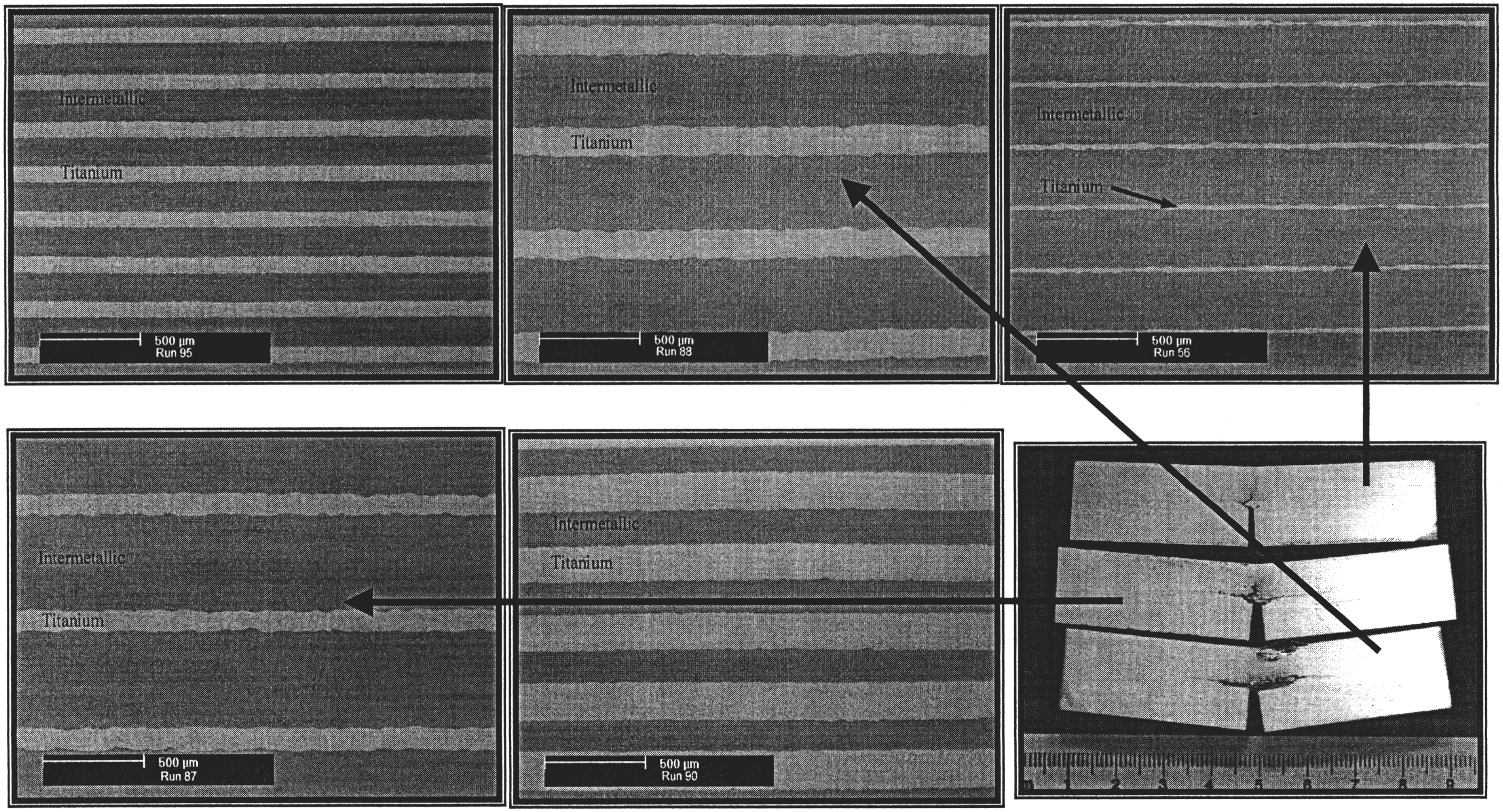


Separate Anode and Cathode Filament Battery



Simulation of Fragment Impact

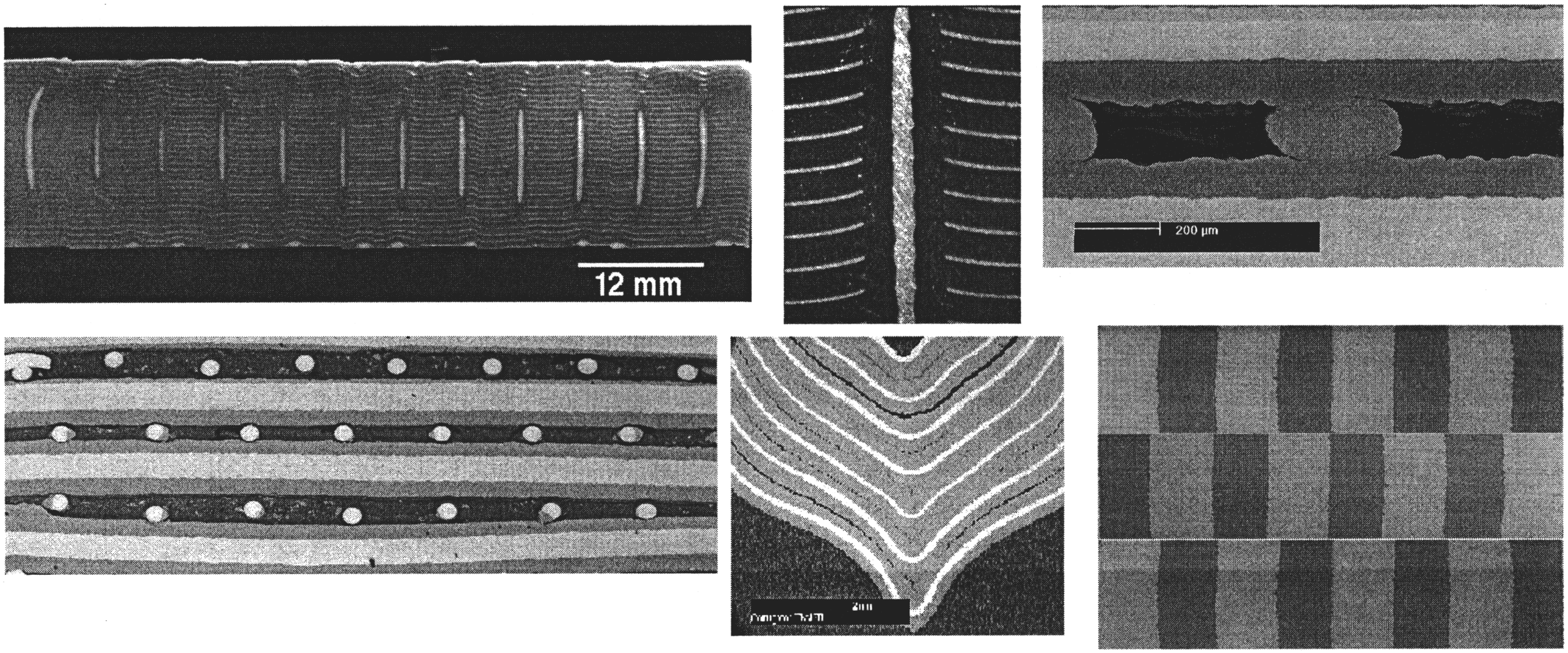
Multifunctional Laminate Material Systems



B-17

UCSD

SMFM: Tunable Structures

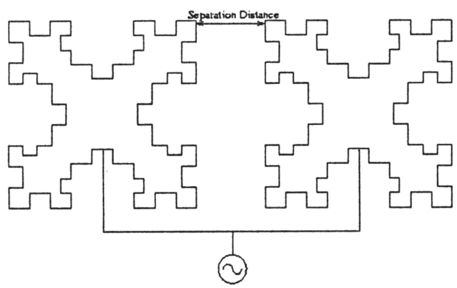


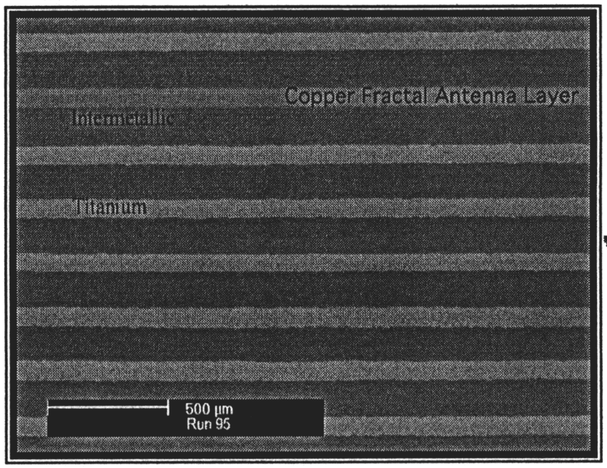
B-18

Morphology design and control can provide:
- **Strength and damage tolerance**
- **Integrated antennas, sensors and actuators**
- **Engineered dampening response**
- **Engineered electromagnetic properties**
- **Chemical sensing capability**

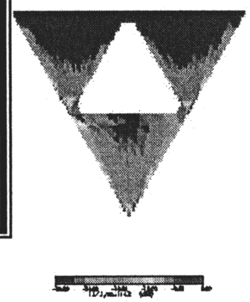
UCSD

SMFM: Integrated Fractal Antennas

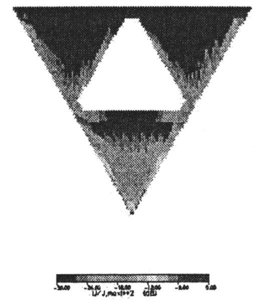


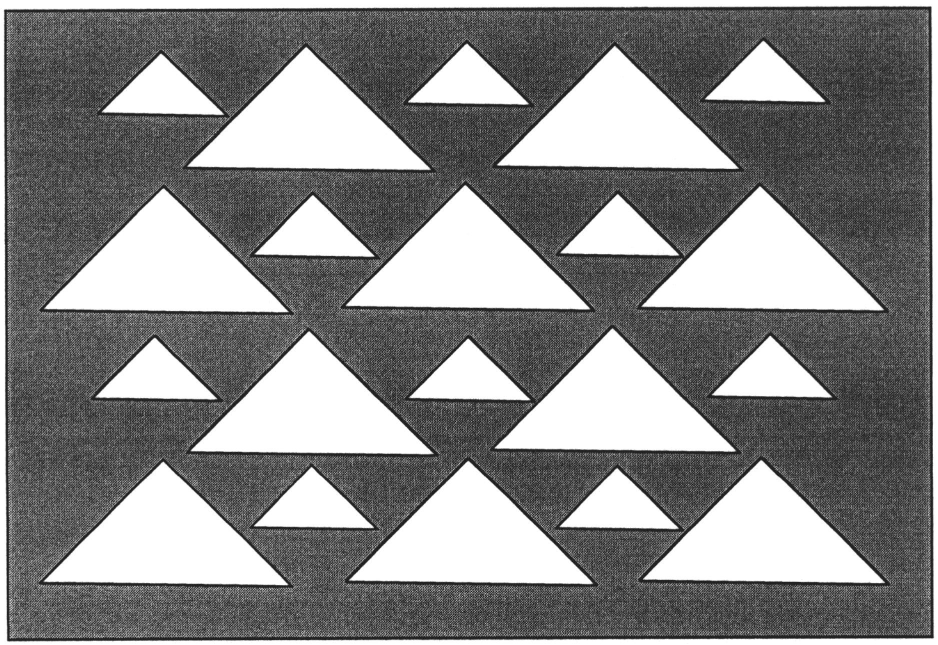


Sierconn0 9.4 GHz

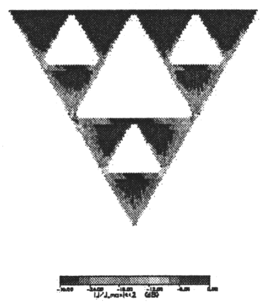


Sierconn0 23.8 GHz

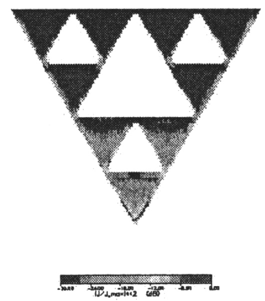




Sierconn1 5GHz



Sierconn1 23.8GHz

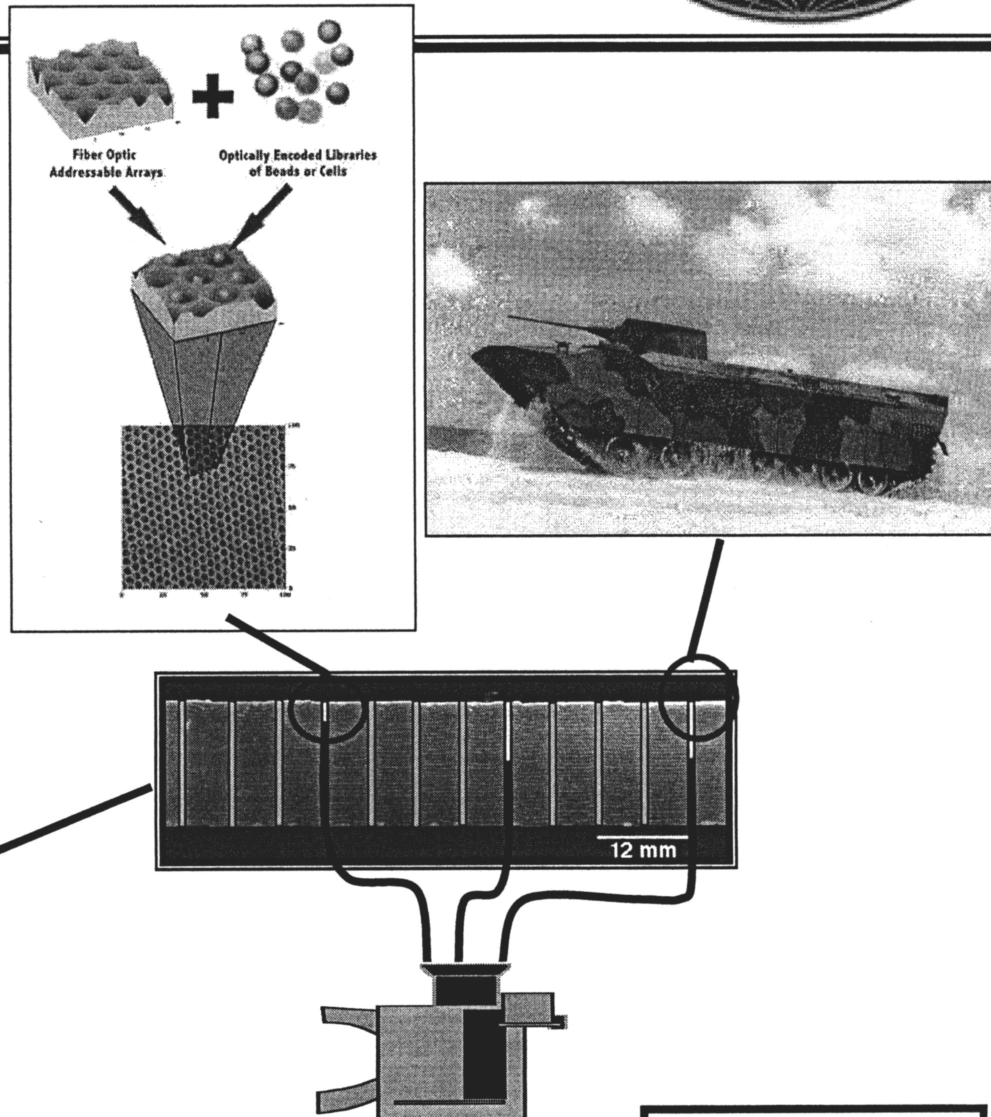


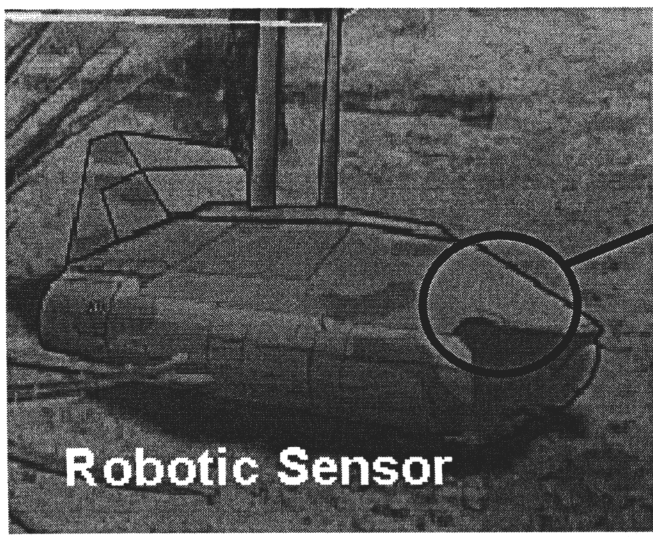
B-19

SMFM: Structure as a Sensor

- Structure with integrated "million eyes" concept. Ability to look continuously in all directions with no surface mounted imaging
- Structure with "chemical environment" sensors

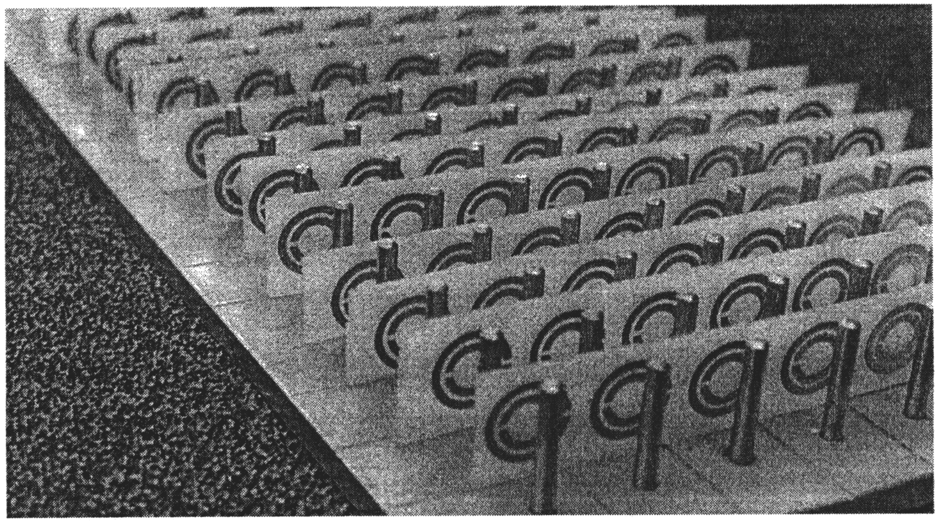
B-20



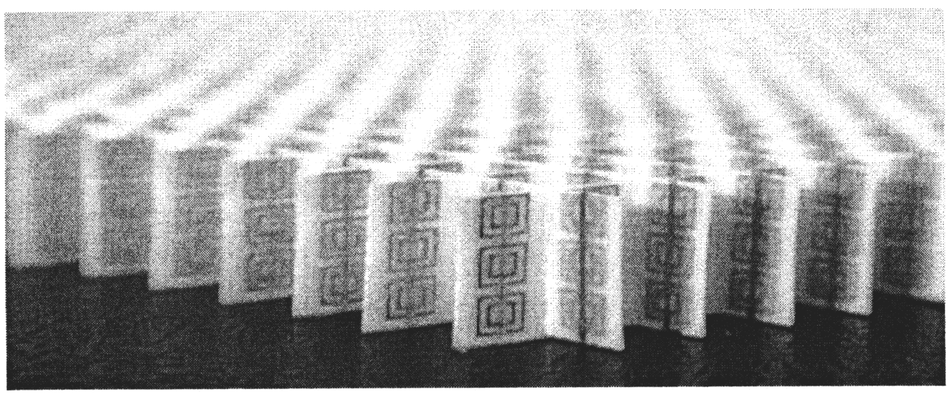


UCSD

Left Handed Materials



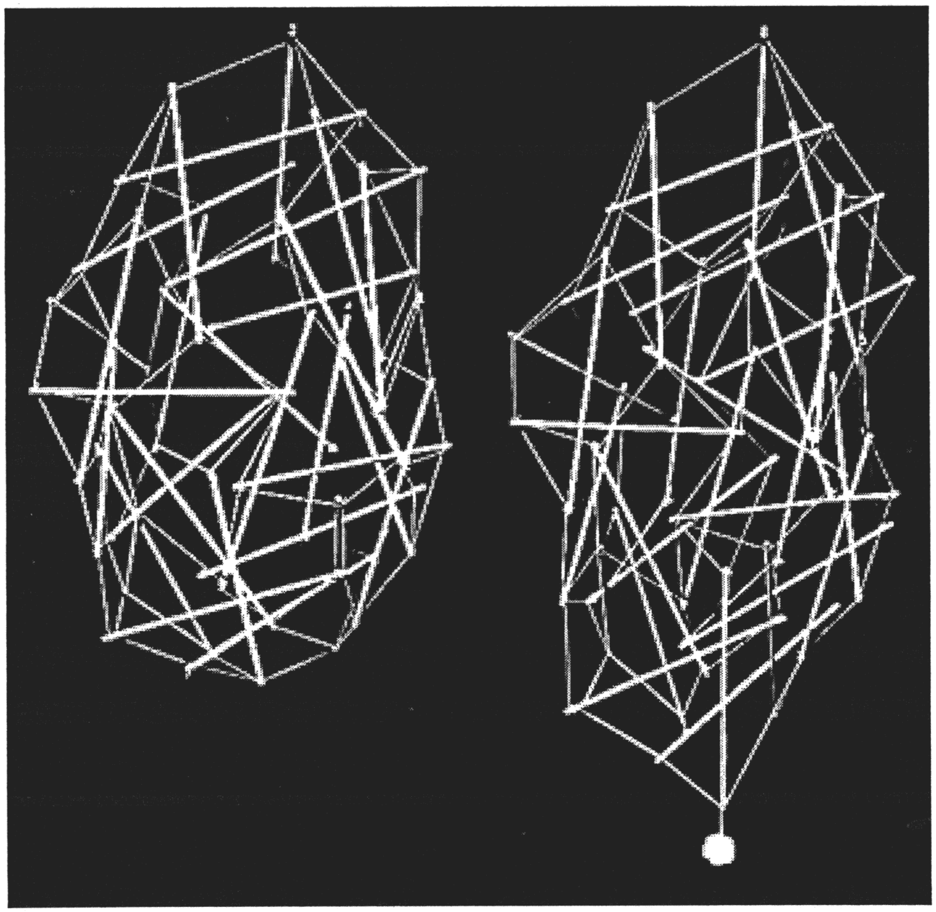
- Engineered chemical and morphological control allows for controlled properties
- Theoretically predicted
- Experimentally verified (ref: Schultz et.al. Science, 2000



B-31

UCSD

SMFM Self Adaptive Structures

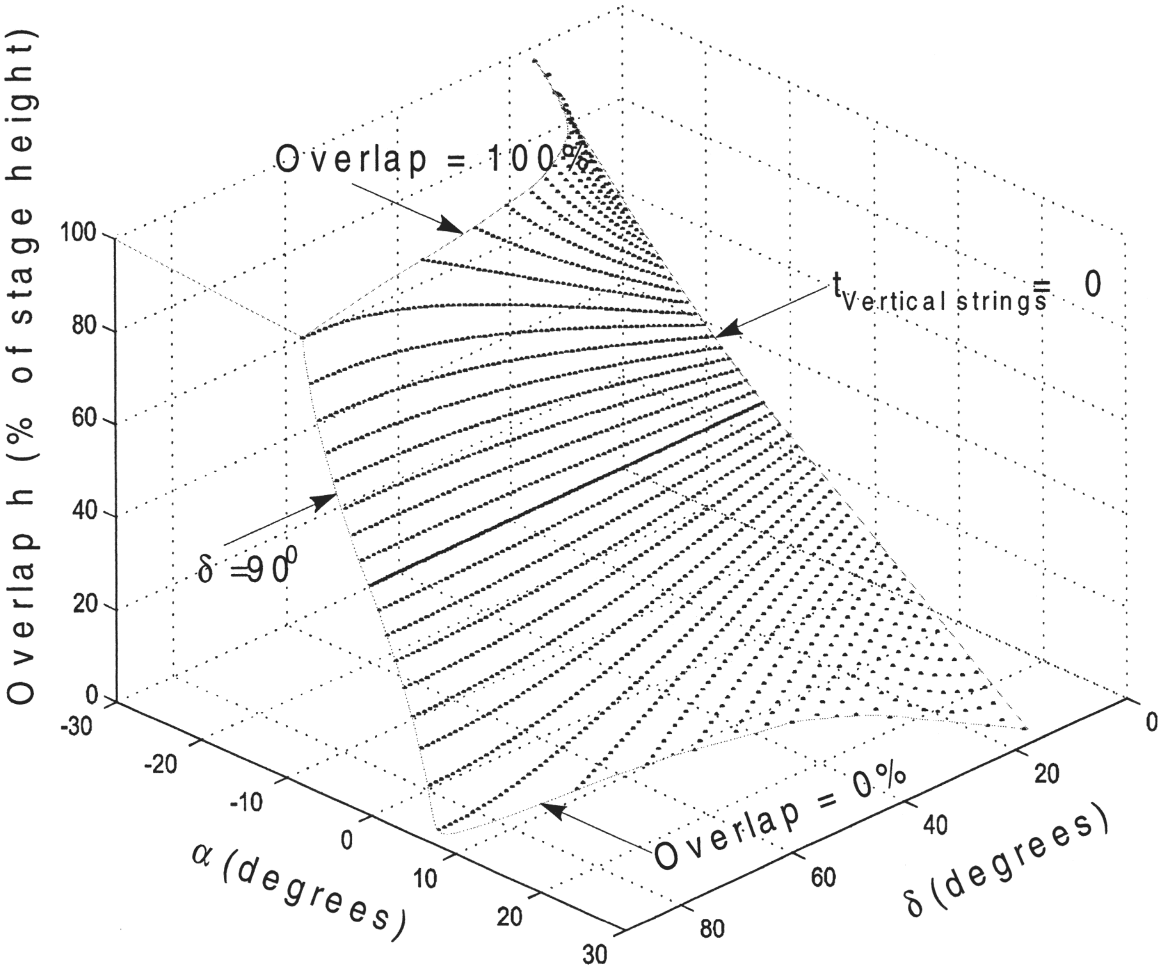


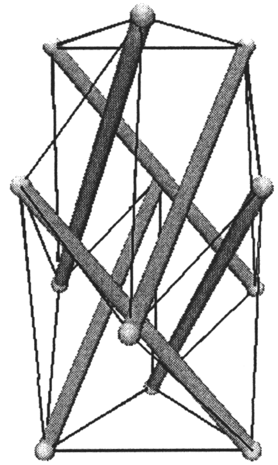
Tensegrity Structures

- **Advanced material systems concepts based on compressive elements stabilized by tensile tendons (TENSEGRITY)**
- **Spatial and stress distributions define behavior of structure**
- **Passive or active response possible. Members serve as actuators, sensors, and structural support**

B-23

SMFM Self Adaptive Structures





- No joints
- No load reversals
- No member bending
- No potential energy change over a large range of states. (In equilibrium over a range of shapes)
- No CPU necessary for control—locally adaptive

B-23

SMFM: Self Healing Strategies

Natures Template

- Detect "not normal" by distributed sensors and autonomous roving monitors
- Two stage processes: "temporary patch" then "remodel for permanent repair"
- Dynamic system (not equilibrium)
  - Materials (proteins, cells) that can be formed/removed under dynamic state
  - "Futile cycle" strategy: repair/healing is an extension of remodeling/maintenance
  - Shed, re-grow, ablate
- Fluids for mass transport
- 'Smart', autonomous and mobile particles/systems
- 'Smart' membranes

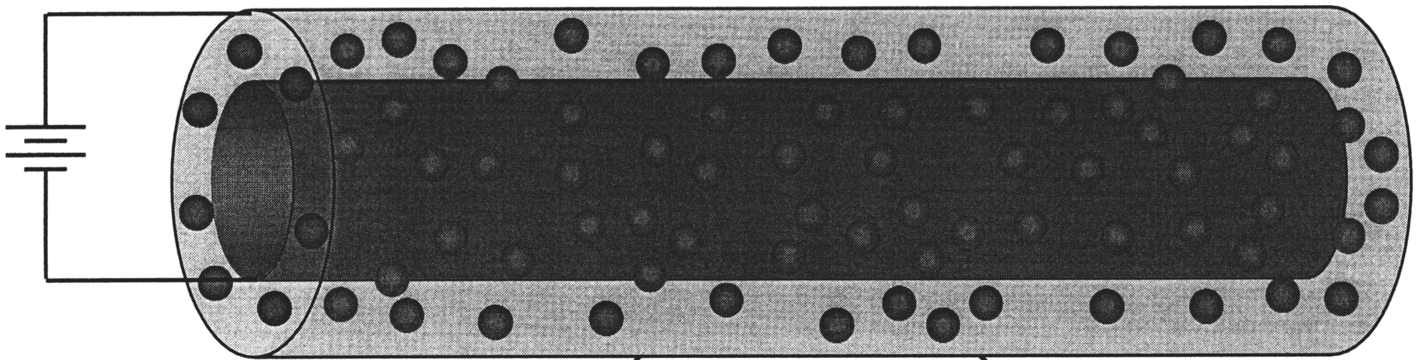
Synthetic 'Toolbox'

- Surface tension, energy and activity
- Osmotic pressure
- Switchable systems (liquid crystals)
- Damage-activated reactions
- Heat generation
- Self-assembly
- Self re-aligning structures
- Structures that shed their surface
- Electrostatically/magnetically/optically actuated/ guided systems
- Negative Poisson ratio systems

Harvard /Princeton

B-34

Self Healing by Electrohydrodynamic Coagulation of Particles



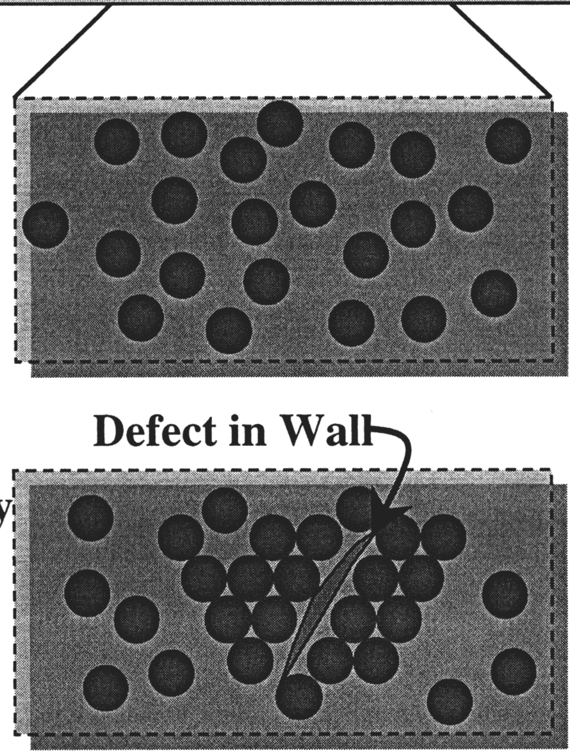
B-25

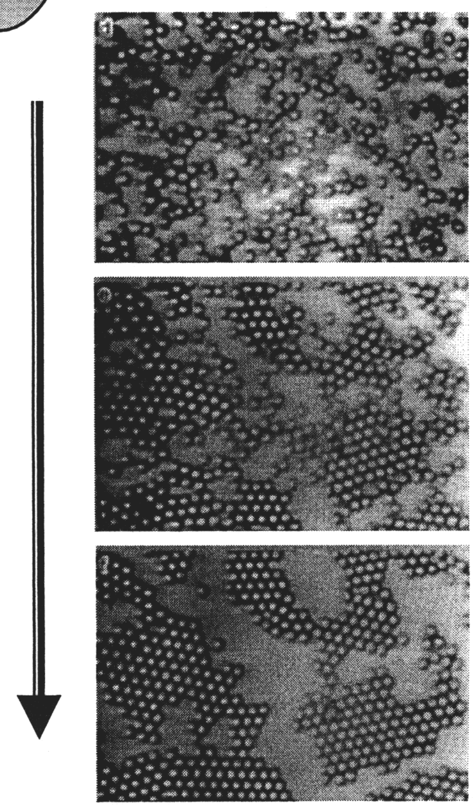
Sub-Critical Current Density

2D Particle "Gas"

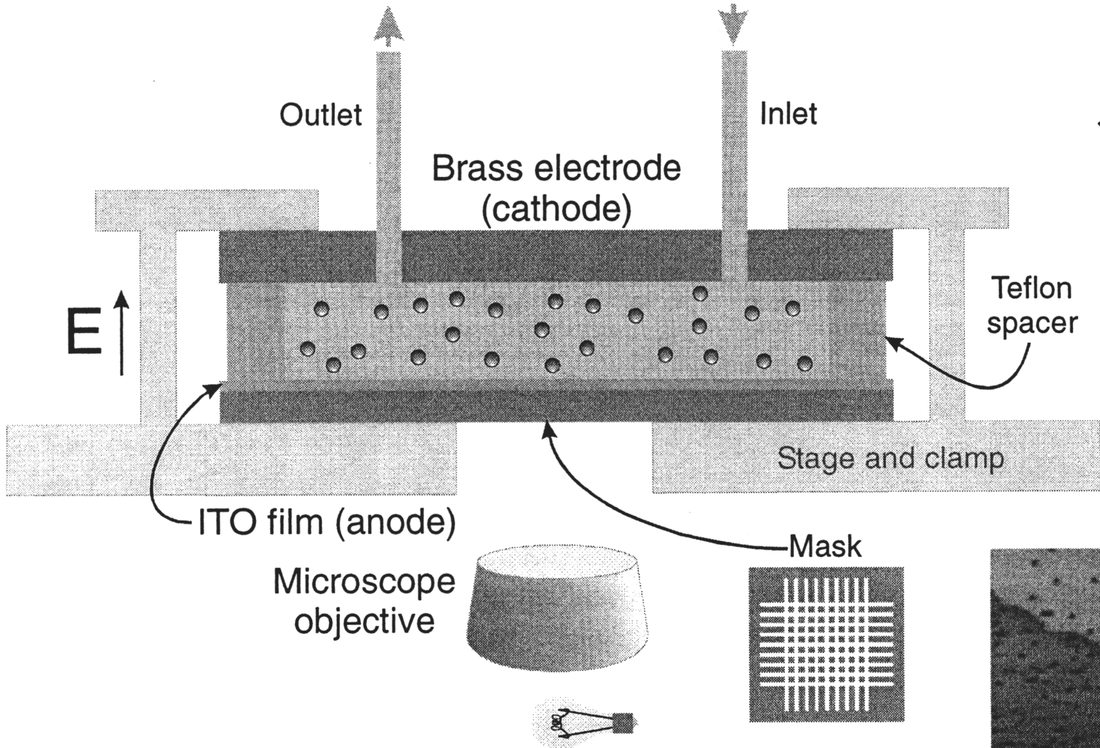
Surface Defect → Increased Current Density

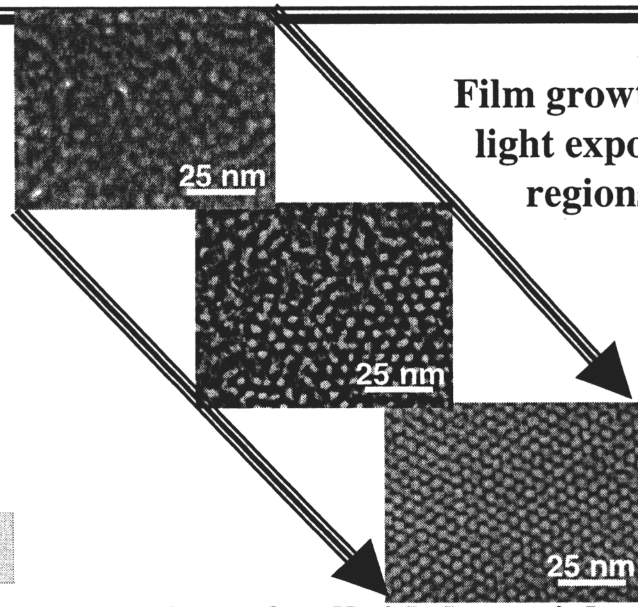
Defect Nucleates Assembly





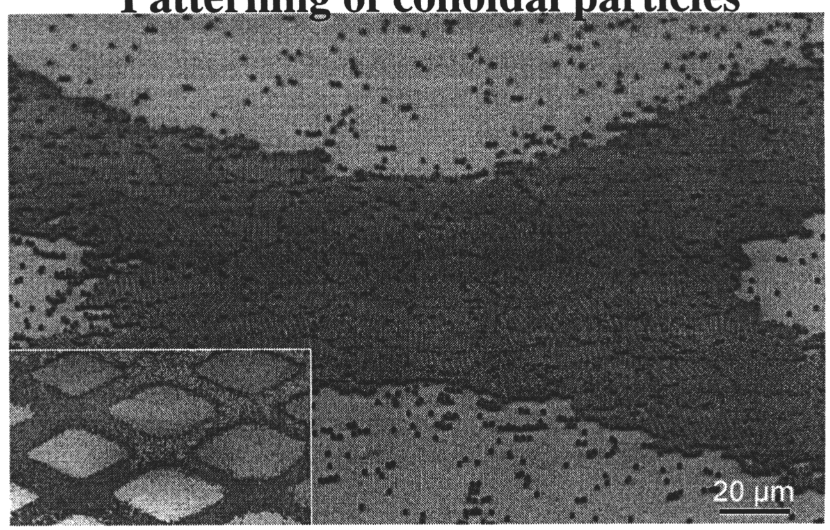
Light-modulated Electrophoretic Self Healing





Film growth on light exposed regions

Patterning of colloidal particles

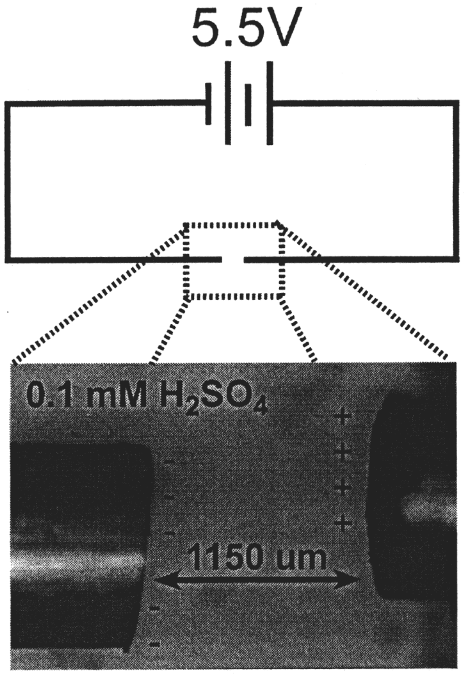


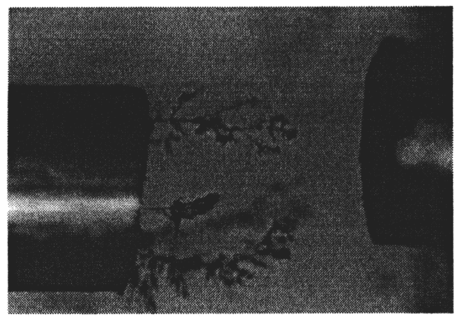
R. C. Hayward, D. A. Saville, and I. A. Aksay, *Nature* **404** 56-9 (2000)

B-26

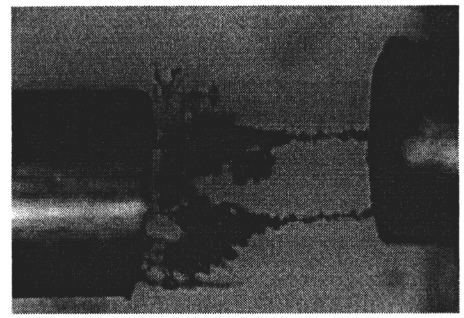
SMFM: Self Repair Systems

B-27





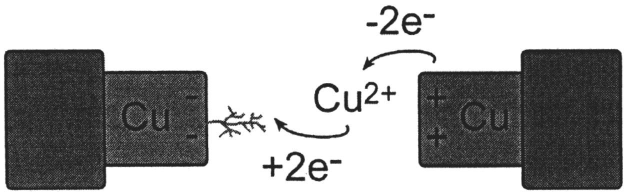
25 sec after applying potential



60 sec after applying potential

- **Electric field directs growth of wire toward the anodic electrode**
- **Growth slows and finally stops as wires make contact and eliminate the potential difference**
- **No external copper source necessary**
- **Should wires break, the potential difference is reestablished and new growth is initiated**

General strategy:

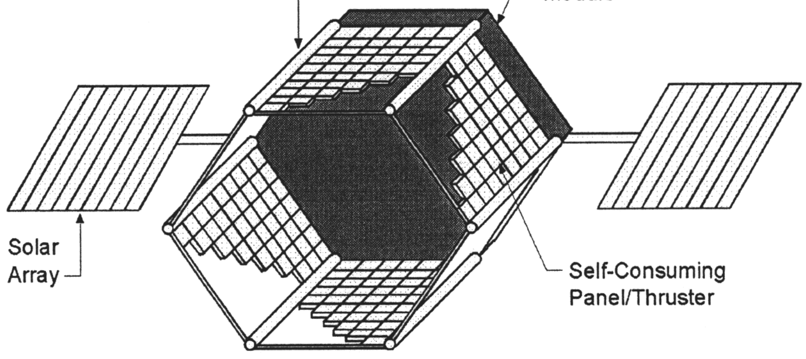


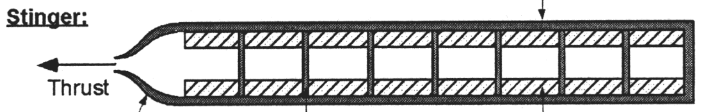
0.1 mM H_2SO_4

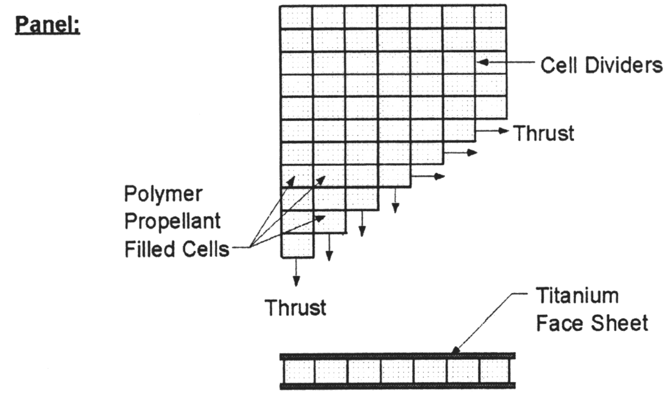
Bradley, J.-C., *et. al. Nature* **389**, 268.

Self Consuming Structures

- **Functions of space system structures**
  - withstand direct launch loads, no function on orbit
  - provide shear strength, radiation shielding, some function on orbit
- **Parts of non-functional structure on orbit may be consumed to produce useful thrust**
  - orbital mobility, especially high thrust/impulse operations
  - end-of-life operations
- **Using excess structural material as propellant will**
  - reduce spacecraft size and weight; less onboard propellant and less structure to contain propellant
  - increase orbital lifetime if structure consumed as additional propellant



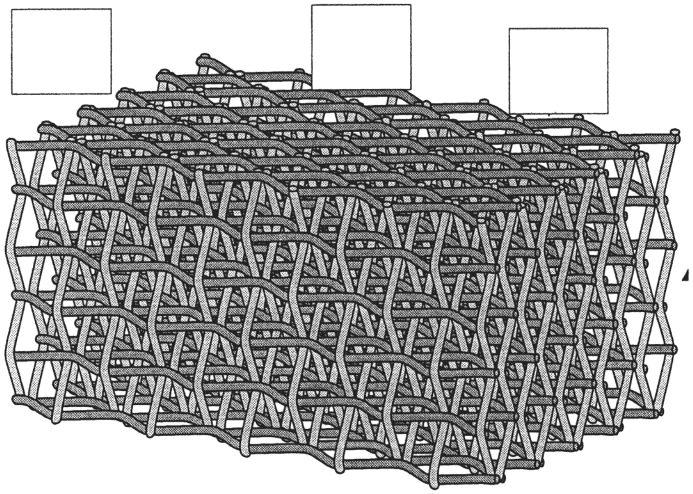


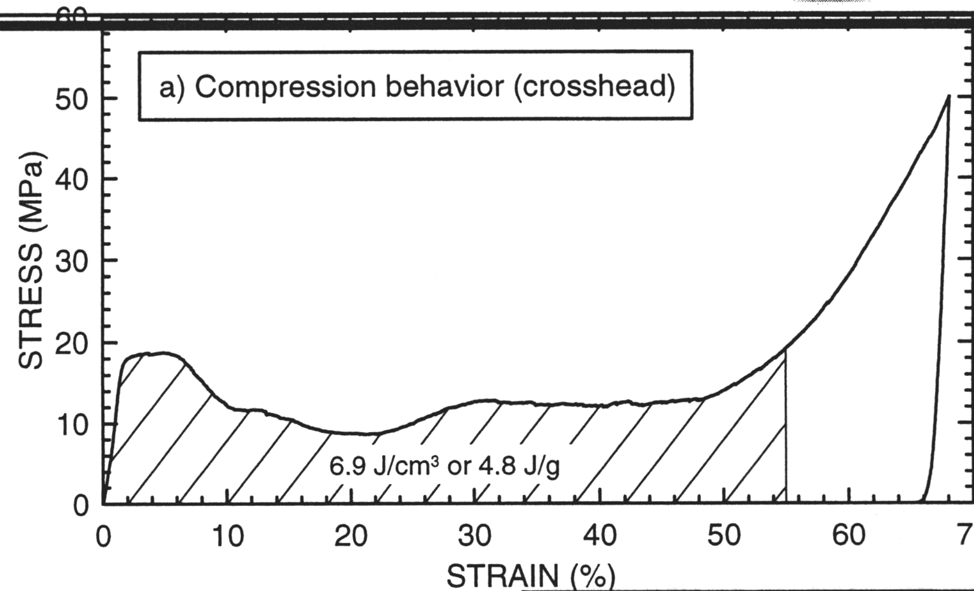


E-0361

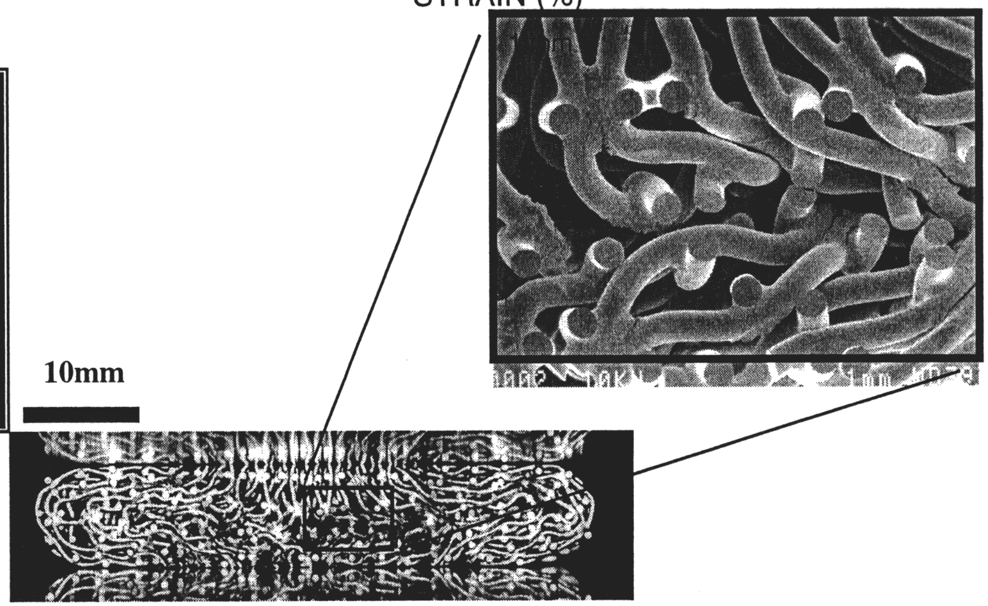
B-28

SMFM: Thermal Control Structures



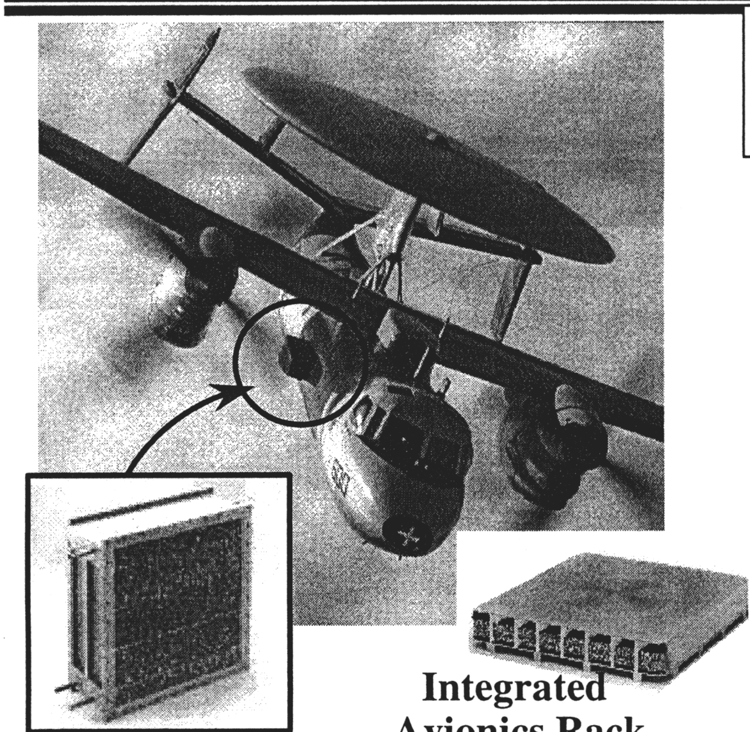


- **Very high structural efficiency**
- **Structures conducive to thermal management**
- **Integrated antennas and actuators**
- **Engineered damage response**
- **Low cost conformal structures**



B-29

SMFM: Thermal Control Structures Transition



Foam Metal Heat Exchanger

Integrated Avionics Rack (internal)

REQUIREMENT

AEW/EW electronics require 3X heat dissipation

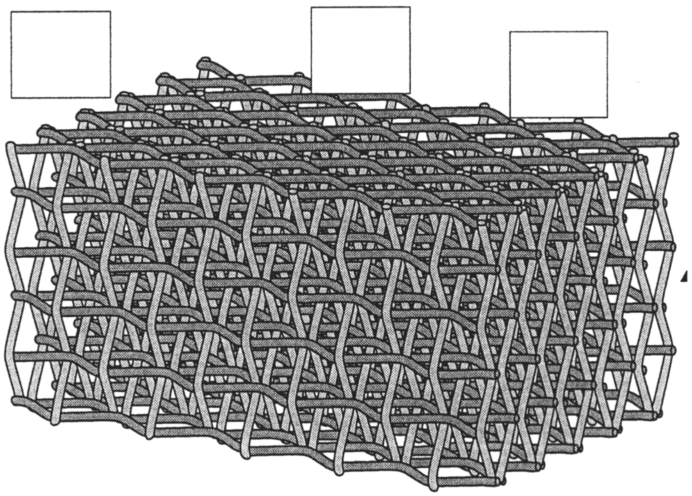
SMFM SOLUTION

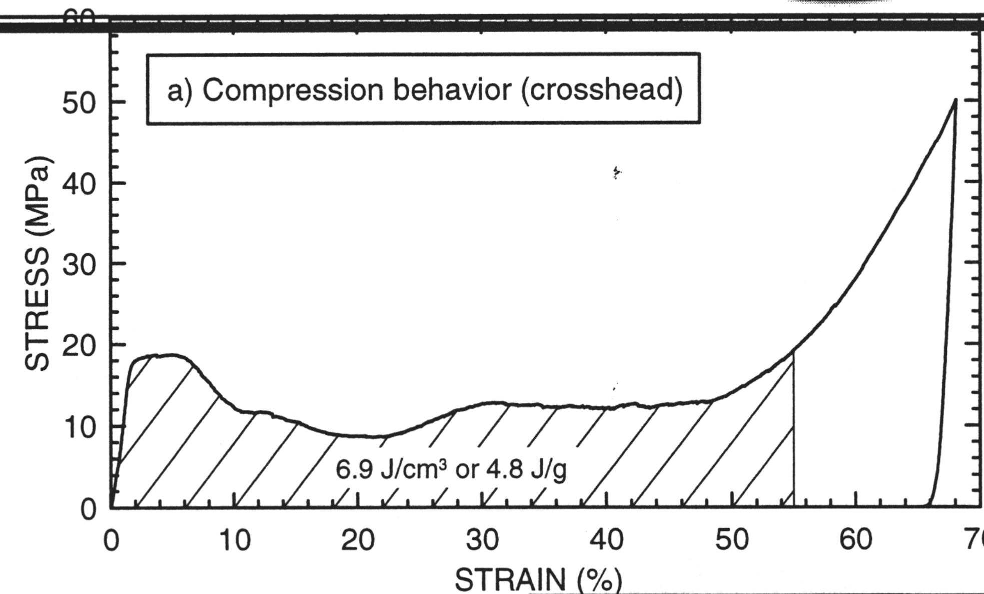
- Advanced foam metal heat exchangers improve efficiency by a factor of 10X.
- Porous metal heat exchangers:
    - 30% Lighter
    - 40% Smaller
    - 10% Less expensive
- New avionics suite with conformal racks and cards.

Program:	Design, Fab. & Test of Heat Exchanger.
	Conceptual Design for EA-6B ICAP-3
Sponsors:	DARPA, Navy and NG (E-2C Program).

SMFM: Thermal Control Structures

B-31





- Very high structural efficiency
- Structures conducive to thermal management
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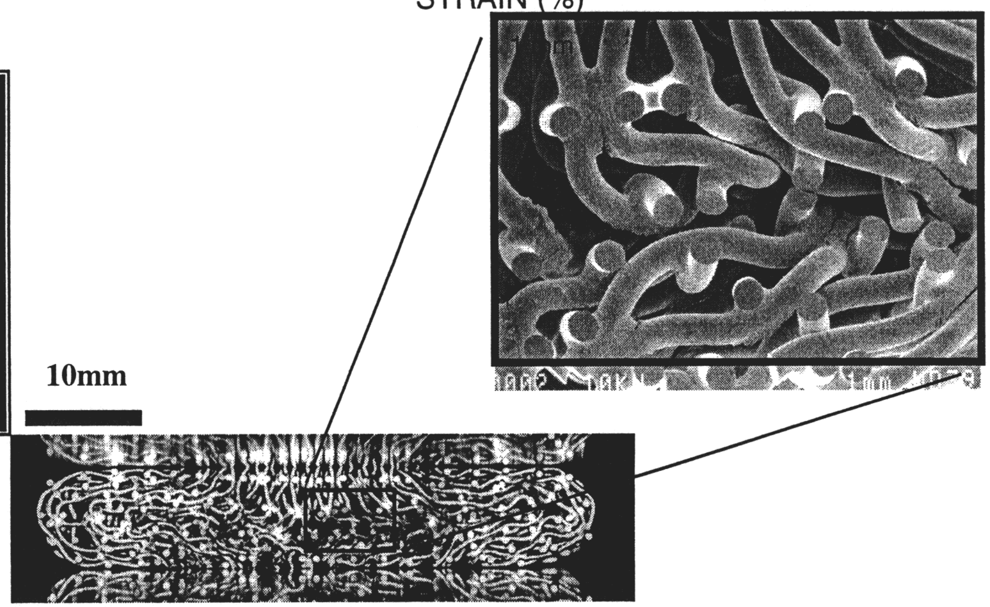
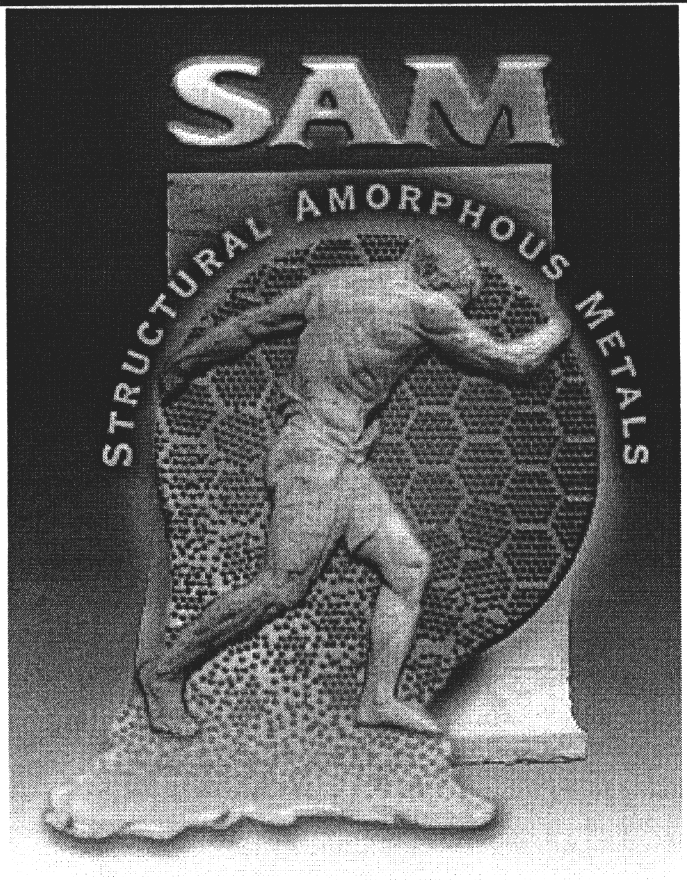
- Low cost conformal structures



13-32



Structural Amorphous Metals

Compelling Opportunity

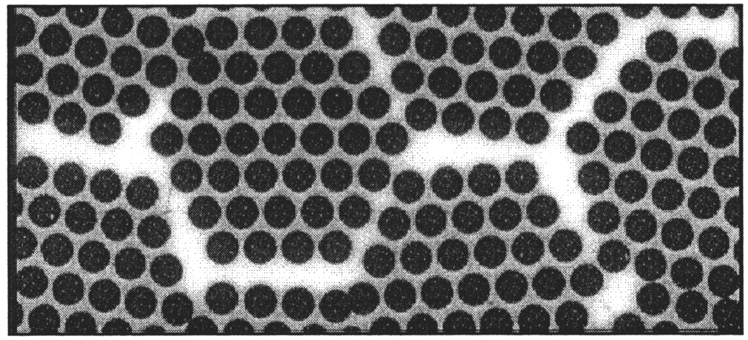
Structural Amorphous Metals

- A new class of materials with a radical combination of properties
- There are unique, compelling and enabling applications in several key DoD areas (e.g. ship hulls, aircraft structures, penetrators, etc.)
- DARPA aims to develop the science and technology of this field, and demonstrate its utility in example challenge problems

Amorphous Metals are Fundamentally Different to Conventional Metals

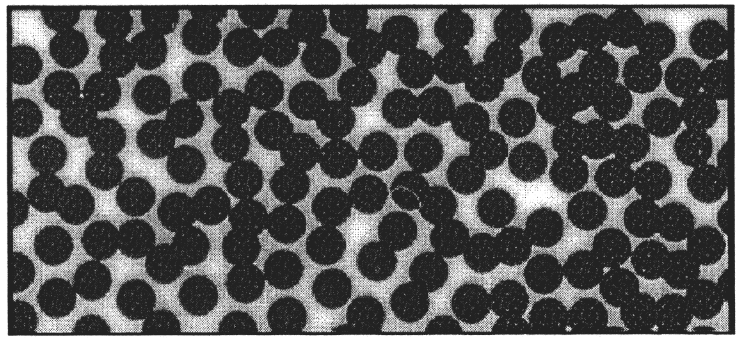
Structural Amorphous Metals

Crystalline (Normal) Metals
- *Long-range order*
- *Grain boundaries*



B-34

Amorphous Metals
- *NO long-range order*
- *NO grain boundaries*

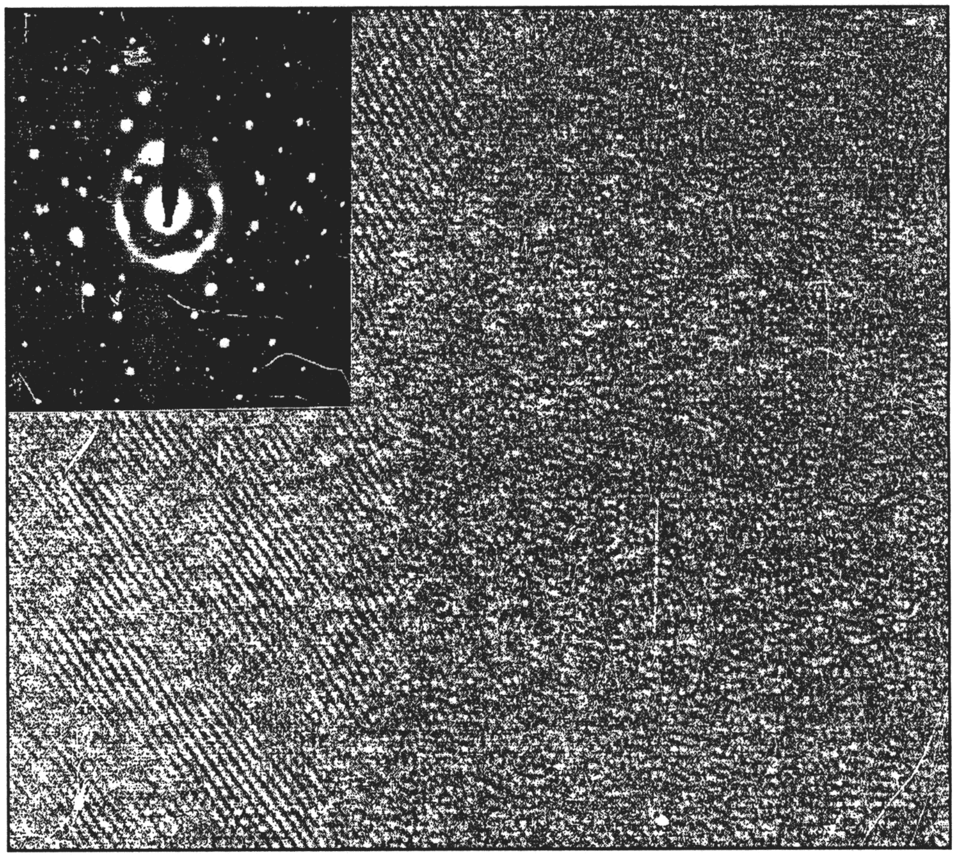


•Amorphous materials exhibit unique properties

Atomic Arrangement in Crystalline and Amorphous Metals

B-35

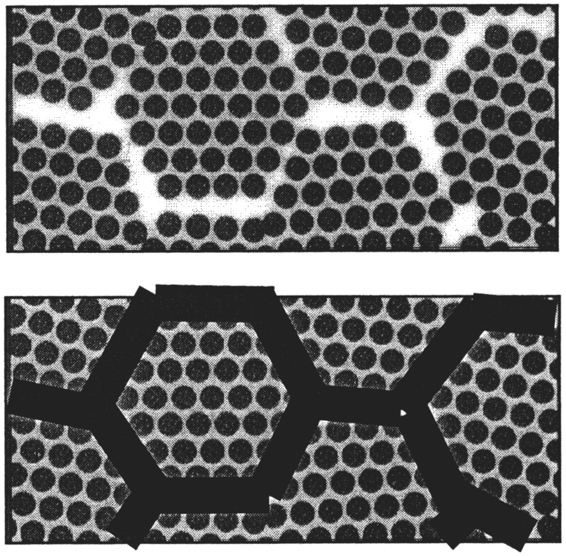
- Micrograph shows:
  - ➢interface between amorphous and crystalline metal
  - ➢atomic planes of crystalline metal
  - ➢random arrangement of amorphous material
  - ➢diffraction information



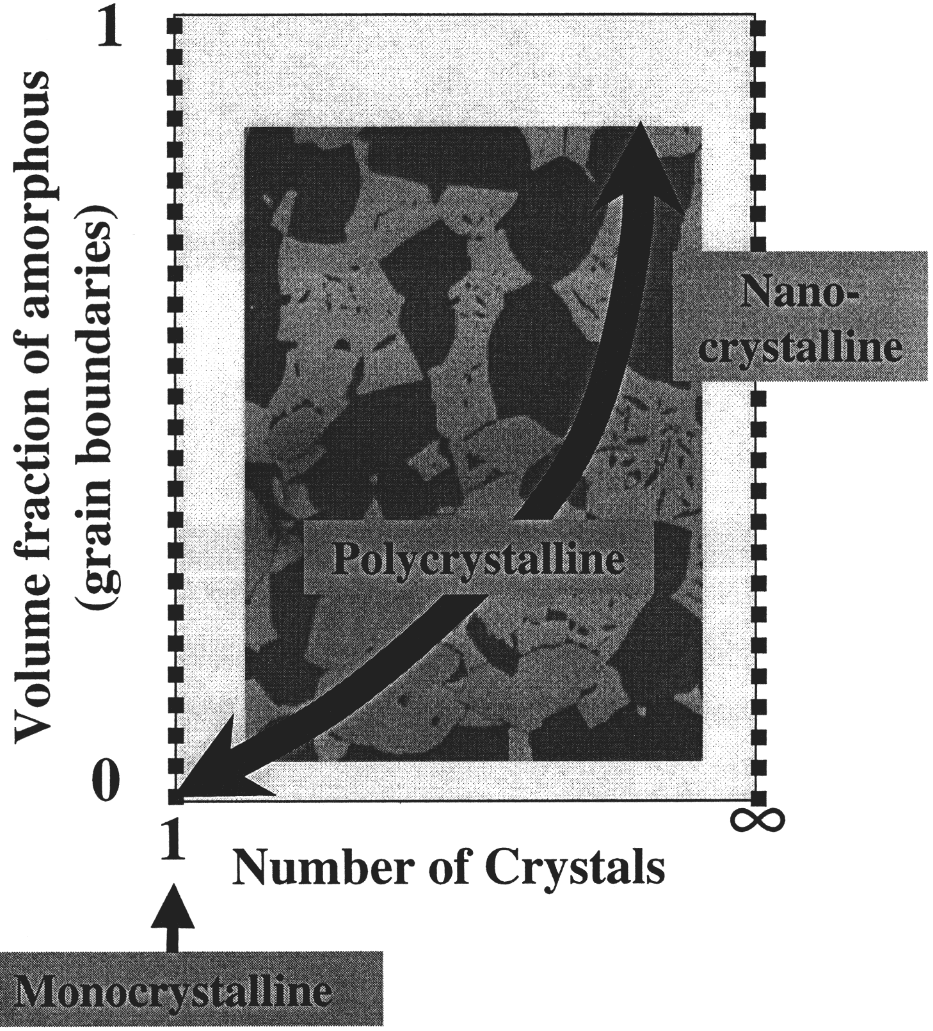
Crystalline Amorphous

Structural Amorphous Metals

Polycrystalline



- **Intersections of grains (grain boundaries) can be considered as "amorphous".**
- **Changes in grain size change the volume fraction of amorphous content**



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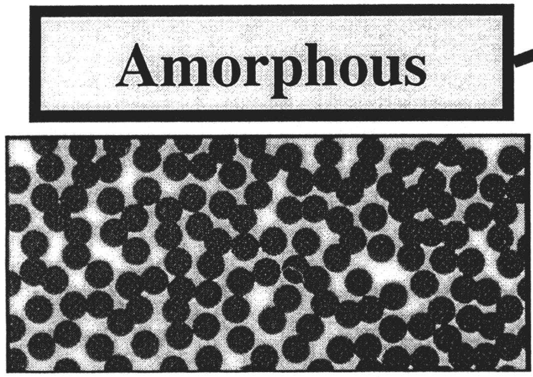
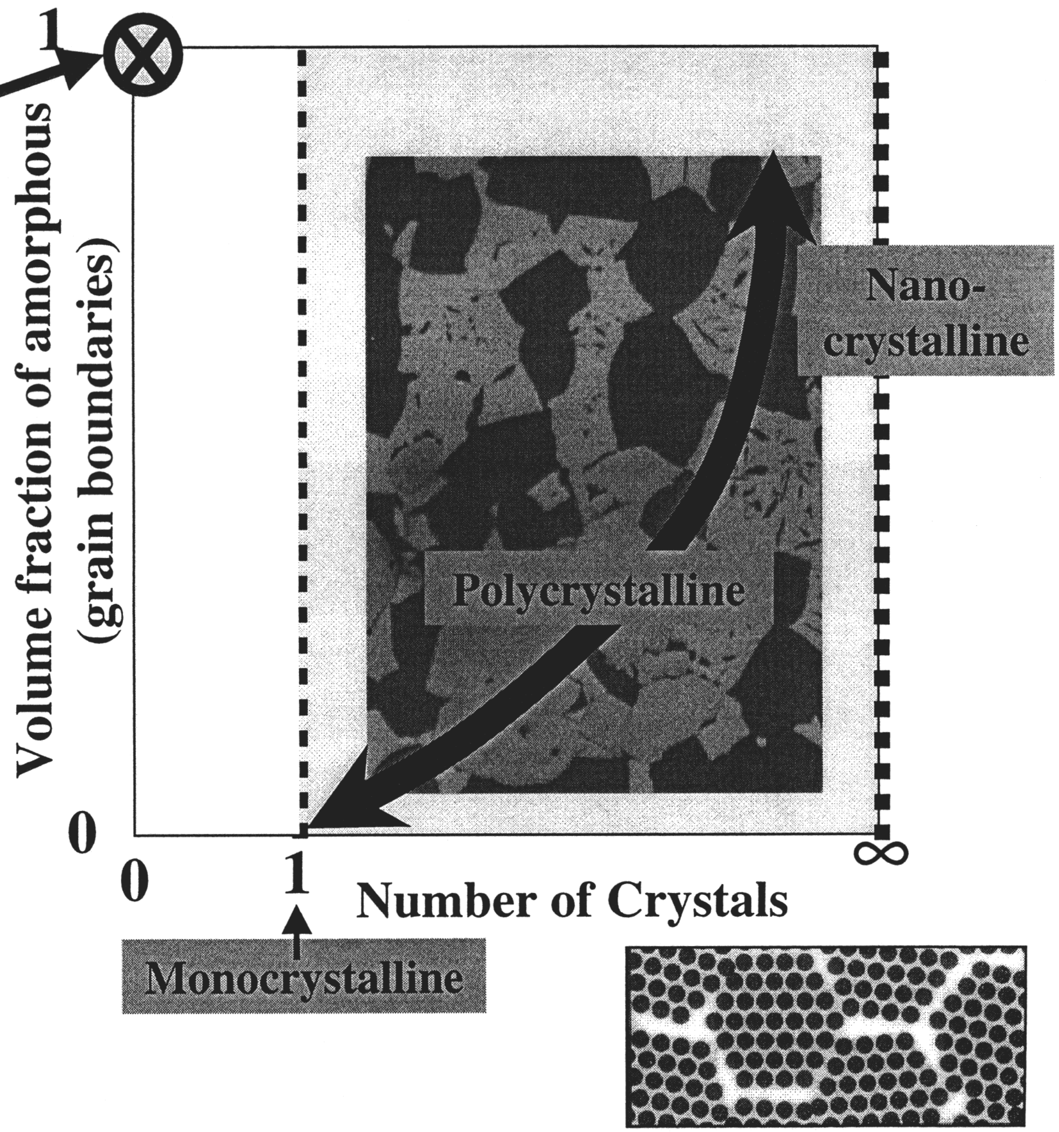
Amorphous Metals Are Truly New



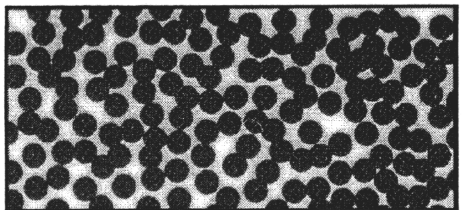


- **Amorphous Metals are NOT confined by limitations of crystalline materials**
- **Such an opportunity has NOT previously existed for structural materials.**

13-37

Transformations of SAM to Crystalline Offer Unprecedented Materials Design Freedom

- Short-range order
- NO grain boundaries



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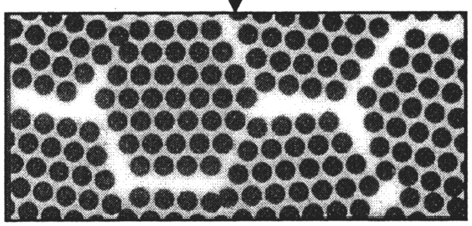
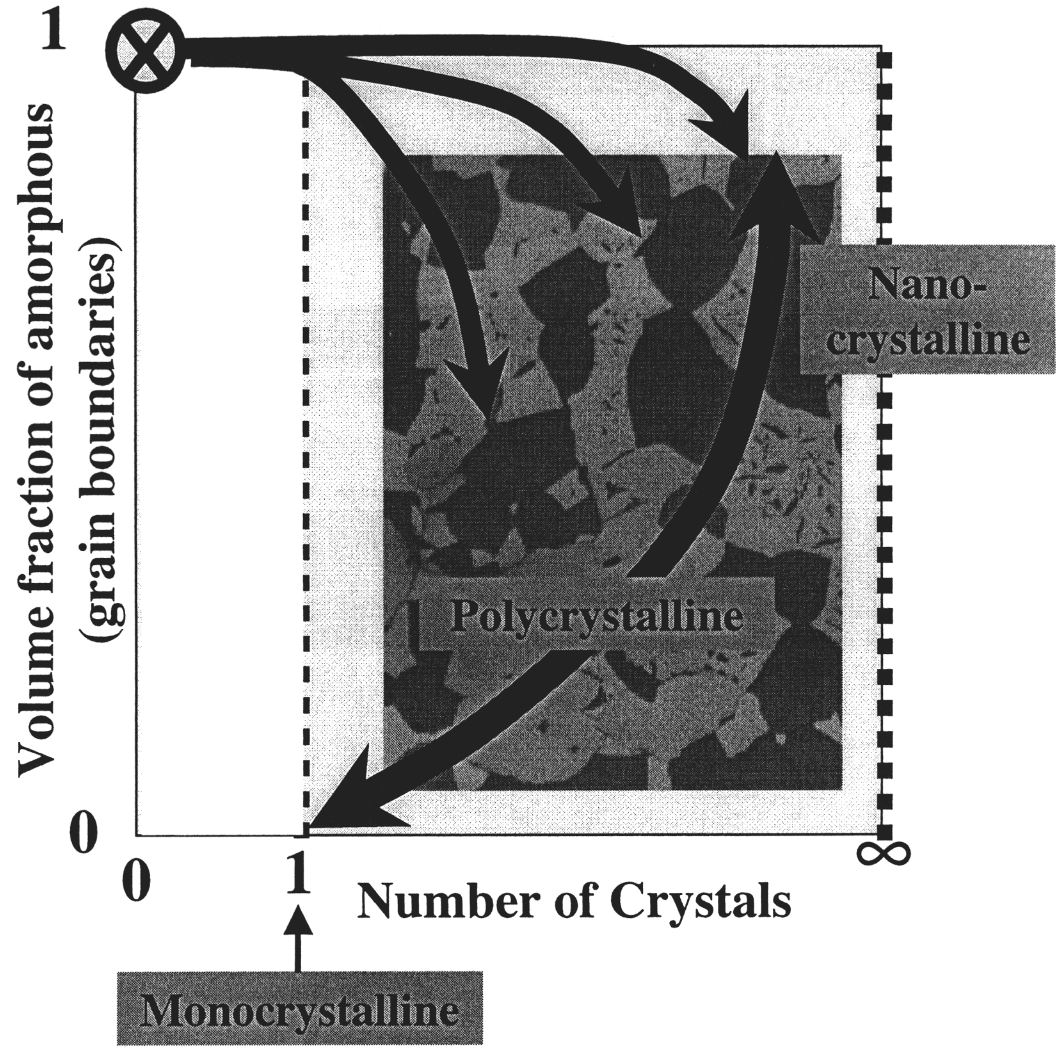
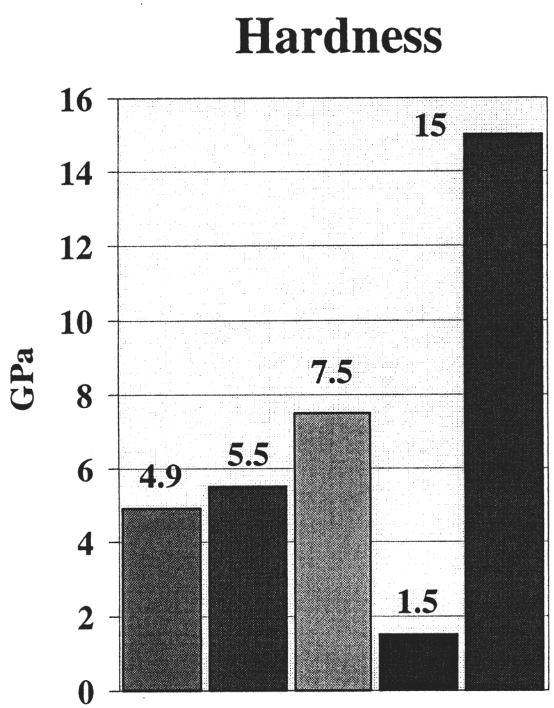
Transition path could be of CRITICAL importance

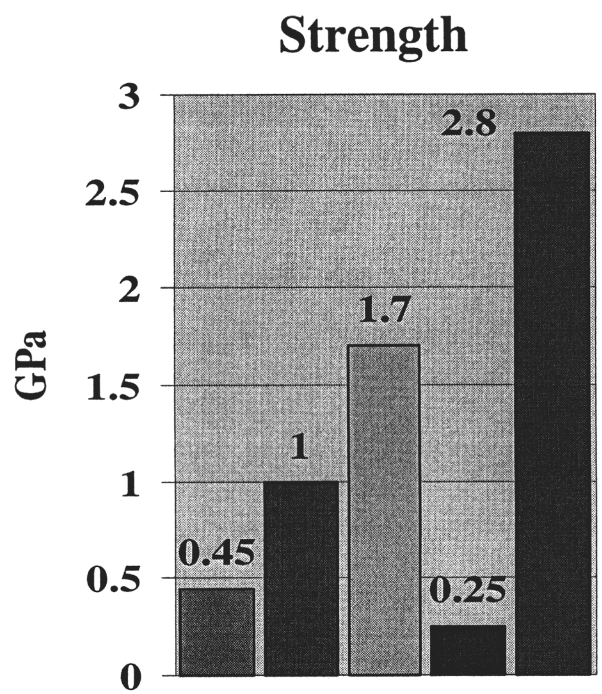


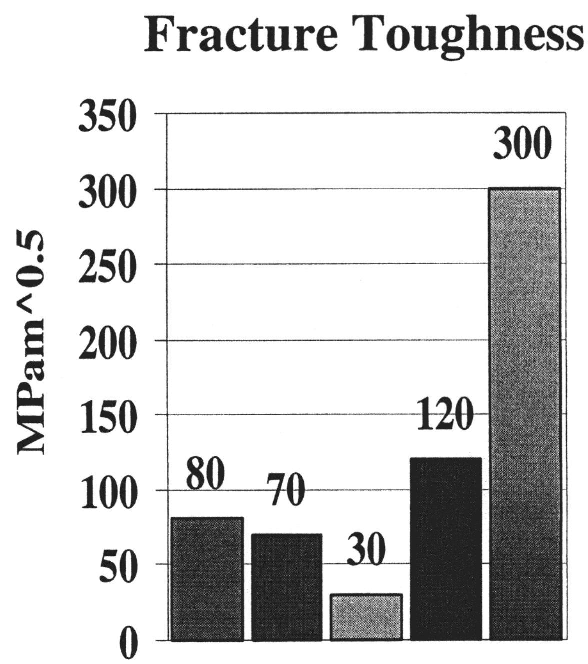
- Long-range order
- Grain boundaries



Why Amorphous Metals?







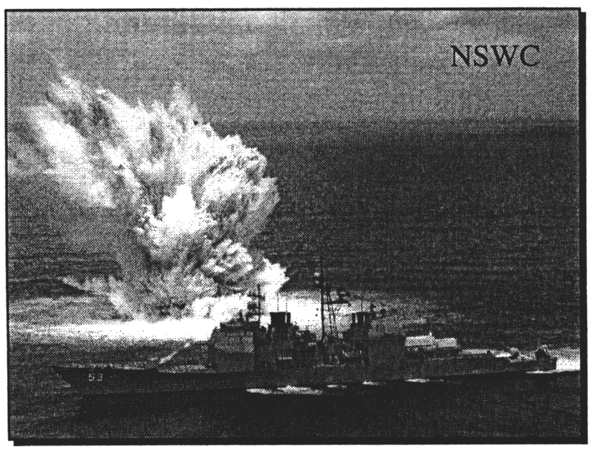
Steels

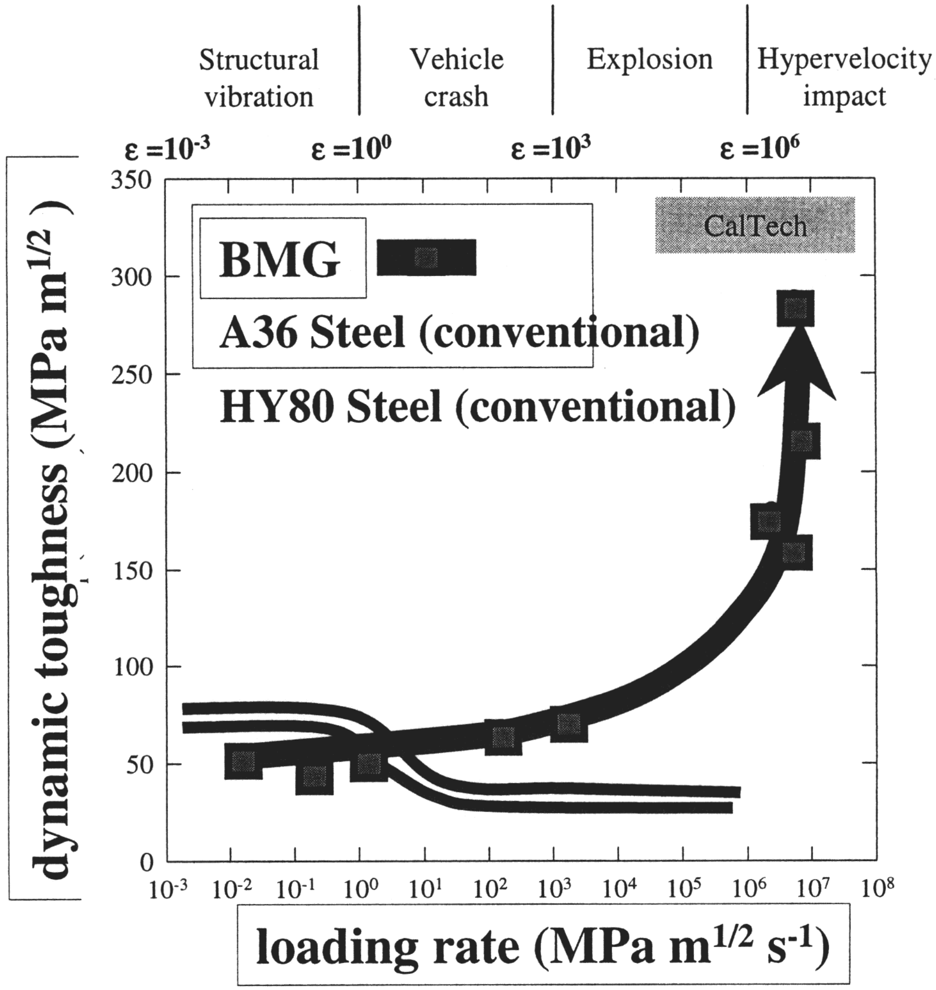
Carbon
High Strength
Tool
Stainless
Amorphous

Amorphous Metals are in a Class of their Own!

Unexpected Strain Rate Response in SAM

- **Dynamic toughness of SAM is <u>EXACTLY</u> the opposite of conventional materials -- toughness increases with strain rate**
- **Conventional materials exhibit reduced toughness with increasing strain rate**
- **<u>Speculate</u> that combination of high strength, hardness and dynamic fracture behavior will translate into useful naval and other structures**





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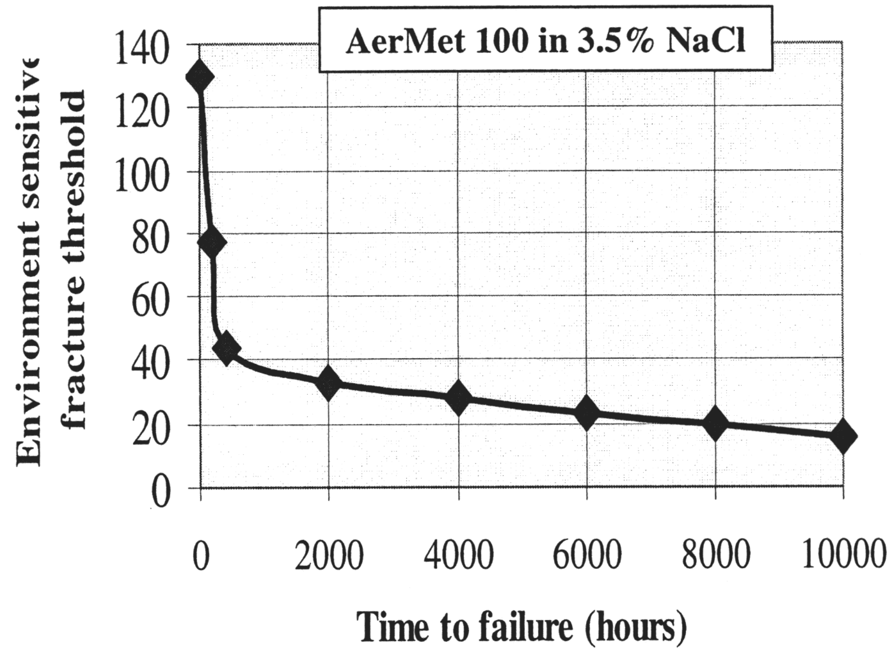
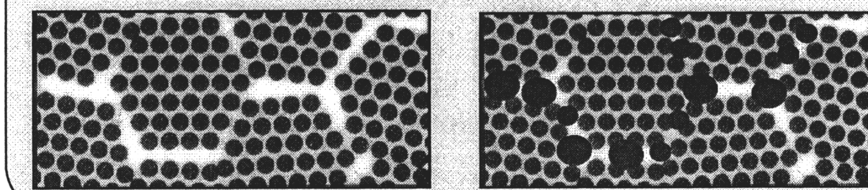
Wear and Corrosion

B-41



Crystalline Localized Corrosion



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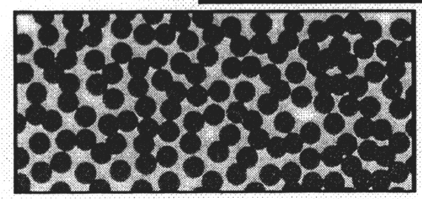

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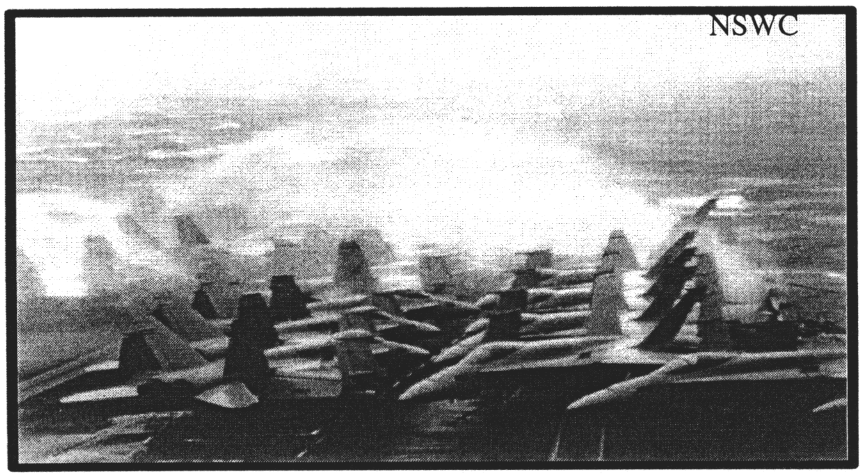


Amorphous Materials;

- **Do NOT have grain boundaries (NO corrosion initiation sites)**
- **Very high wear resistance (better than Si_3N_4)**
- **Damage tolerant**

Accelerated Insertion of Materials InitiativeS. Wax & L. Christodoulou

DARPA/DSO

R. Meilunas (NAWC AD) and R. Dutton (AFRL)

Program Status

Awards of 15- month "Base Programs" to three teams lead by:

1. **Boeing Company (PMC)**
2. **Pratt and Whitney (Metal)**
3. **GE Aircraft Engines (Metal)**

DARPA and its Agents (NAWC and AFRL) rationale for multiple base program awards of 15-month duration is to allow the performers to achieve substantial progress in their AIM concepts and to demonstrate the viability of their approach. It is anticipated that after this initial 15-month period DARPA will down-select to those programs that have demonstrated the optimum strategy, accomplished significant progress, and offer the greatest likelihood to meet the overall AIM program objectives.

Perspective

AIM is a focused mathematics- and computation-intensive materials initiative directed to address a DoD need:

<u>It is intended to:</u>

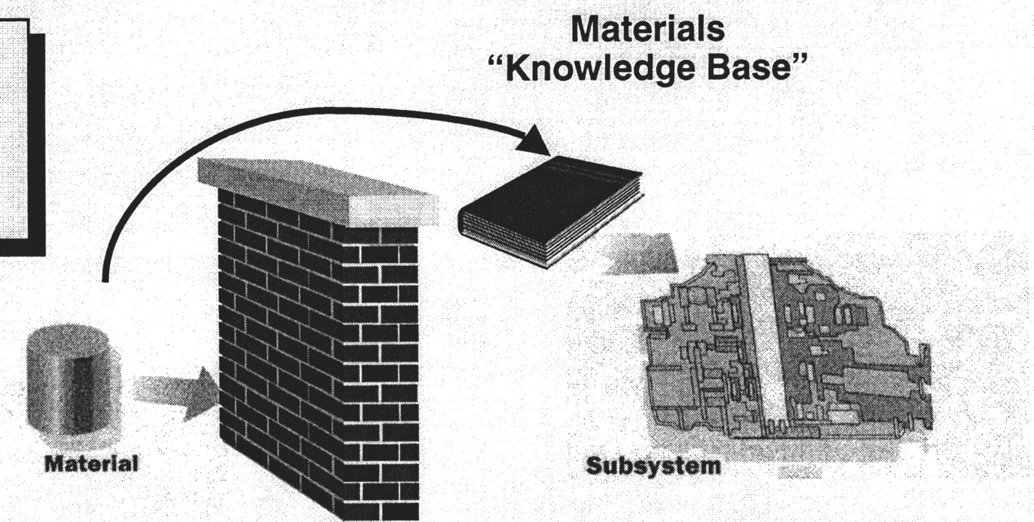
- **Establish a methodology for increasing the speed of material insertion into new systems**
- **Reduce the cost of such insertions**
- **Reduce the risk of using new materials or employing in new applications**
- **Reduce the materials/system design gap**

<u>It is not:</u>

- **A modeling program**
- **A materials design/processing activity**

The Disconnect!

Significant Disconnect Between Materials Development and the Design/Use of Materials in Components/Systems



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Materials Development

- Highly Empirical
- Testing Independent of Use
- Existing Models Unlinked
  - Known Alloy to Reliable Part - 36 Months
  - Steels for Navy Landing Gear - 15+ Years
  - Lightweight Composites for Army Vehicles - 15+ Years
  - Ceramics for Engines - 20+++ Years
  - Changing Ship Steels - 7-10 Years

Systems Design

- Materials Input from "Knowledge Base" of Data (Data Sheets, Graphs, Heuristics, Experience, etc.)
- System/Sub-System Design is Heavily Computational and Rapid
  - Clean Sheet of Paper to Engine Design - 30 Months
- Well Established Testing Protocols

The Problem

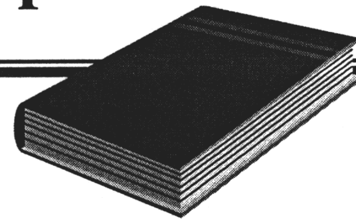
- Current, Empirical Approach to Materials Development is Time (& Cost) Intensive
  - Small, Cautious Steps in Compositional Variations, Scale-up and Processing Changes
  - Multiple Iterations Produce Limited (Non-statistical) Data
  - Early Concentration on "Primary" Properties
  - Does Not Address Designer's Issues and Needs
- Real Insertion Windows Often Open Only for a Short Time
  - Materials Are Seldom "Production Ready"
  - Risk-to-Benefit Too High
- Outcome
  - Designers Choose "Known" Material -- Window Closes!
  - Significant Impact on Performance/Cost of Past and Future Defense Systems

Objective

Establish a methodology for accelerated insertion of materials into defense platforms & structures. Specifically, we intend to:

- **Establish an information-driven quantitative framework for materials development and validation**
- **Orchestrate models, simulations, and experiments to maximize information content**
- **Identify strategies for design using models, computations, and experiments that yield equivalent information**
- **Develop validate and demonstrate tools for accelerated insertion.**

Technical Approach



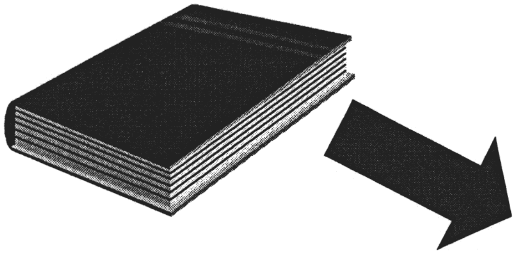
Phase I

- Establish a Design Knowledge Base (DKB) for a currently employed material
- Populate with data from models and/or experiments directed by the new methodology
- Fully integrate into (new or existing) design tools
- Validate against known material database (metals and composites)
- Demonstrate reduction in insertion time

Phase 2

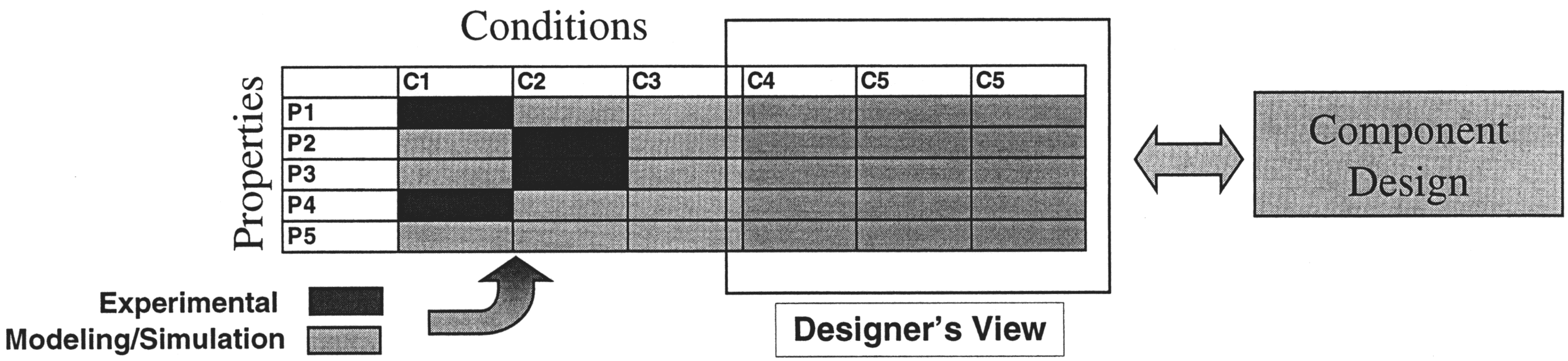
- Establish a DKB for either a new material or an existing material in a new application

“Knowledge Base” Definition



- **<u>Everything designer needs</u> to design a component and decide to use a material**
  - **Validation of critical properties (with confidence limits)**
    - **F (composition, processing, structure, use conditions, ...)**
  - **Confidence in scale-up, design and control of process(es)**
  - **Confidence in manufacture of parts and components (e.G., Weldability)**
  - **Detailed assessment of costs**
  - **Predictable reliability and life**
  - **Etc….**

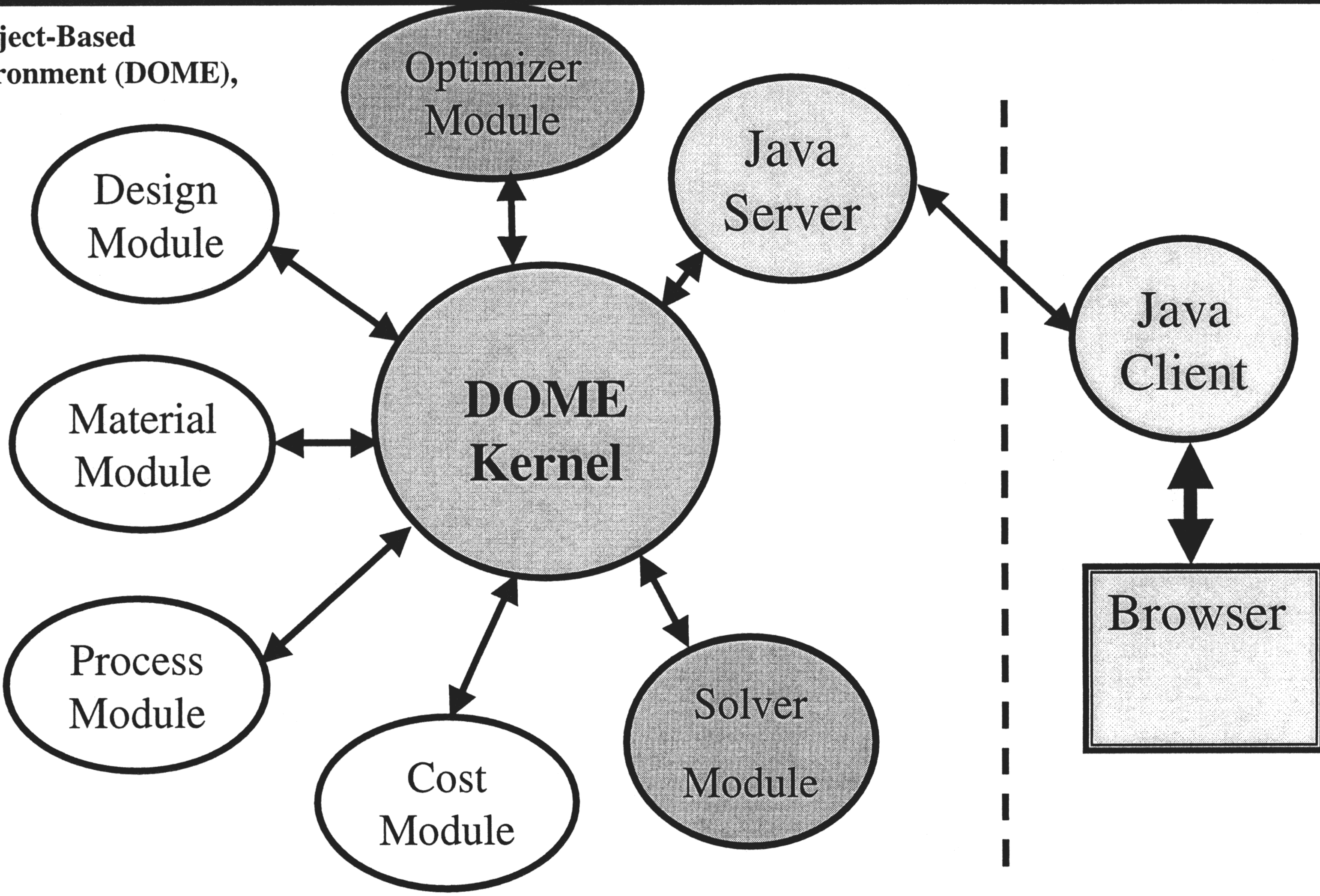
"Knowledge Base" Construction Issues



- **<u>R&D Driven by:</u>**
  - **Necessary "Information" and Its Needed Accuracy for Component Design and Use**
  - **Connectivity Between Knowledge Base Data and Component Design Models**
- **<u>Use of Experiment or Models Transparent to User!</u>**

Example of an "Object-oriented" Modular Approach

Distributed Object-Based Modeling Environment (DOME), MIT



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Adapted form: Nicola Senin, Roberto Groppetti, A. Rossi, David R. Wallace, Integrating Manufacturing Simulation Tools Using Distributed Object Technology, 4th IEEE/IFIP International Conference on Information Technology for BALANCED AUTOMATION SYSTEMS in Production and Transportation, Berlin, September, 2000.

Challenges and Issues - Uncertainty

- Estimation of error and uncertainty as function of physical or mathematical complexity.
- Development of formulations that minimize sensitivity or are insensitive to uncertainty.
- How to collect data to determine, minimize or control uncertainty?
- Uncertainty reduction schemes using high fidelity information "fusion" from low fidelity sources.
- Exploitation of knowledge of uncertainty.

Uncertainty Sources

- Model errors
  - Parametric and nonparametric sources
  - Initial formulation or hypotheses
  - Model reduction
  - Unknown sources of uncertainty
- Data
  - Input uncertainties
  - Numerical errors and uncertainty
  - Experimental accuracy
- Propagation of uncertainty

Quantifying Uncertainty Is Critical to Reliable and Robust Design

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Materials and Manufacturing Technology

Overview for Supersonic Applications

26 June 2001

Edward Hermes

Materials and Manufacturing Directorate

AFRL/MLSC

937-904-5046

edward.hermes@wpafb.af.mil

ML Mission / Vision

B-54

Plan and execute the USAF program for materials and manufacturing in the areas of basic research, exploratory development, advanced development and industrial preparedness. Provide responsive support to Air Force product centers, logistics centers, and operating commands to solve system and deployment related problems and to transfer expertise.

Aerospace materials and manufacturing leadership for the Air Force and the nation.

Current Core Technology Areas (CTAs)

B-55

- Polymers
- Metals
- Organic Matrix Composites
- NDE
- Ceramics
- Tribology/Coatings
- M&P for Sensors
- Laser Hardened Materials
- Manufacturing Technology
- Systems Support
- Air Expeditionary Forces (AEF) Technologies

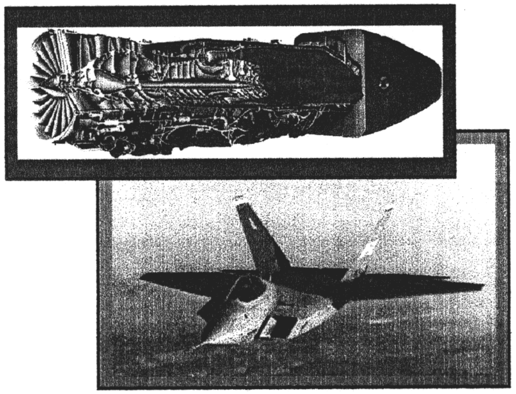
CTA Leaders

B-56

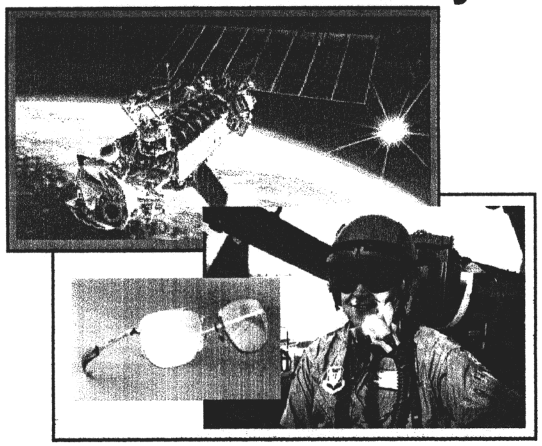
Polymers	Dr. Bob Evers	AFRL/MLBP	937-255-9158
Metals	Ms. Kathy Stevens	AFRL/MLLM	937-255-1305
Organic Matrix Composites	Mr. Scott Theibert	AFRL/MLBC	937-255-9070
Nondestructive Evaluation	Dr. Jim Malas	AFRL/MLLP	937-255-9802
Tribology and Coatings	Dr. Jeff Zabinski	AFRL/MLBT	937-255-4860
Ceramics	Dr. Allan Katz	AFRL/MLLN	937-255-1351
M&P for Sensors	Mr. Bob Denison	AFRL/MLPO	937-255-4474x3208
Laser Hardened Materials	Lt Col Bill Cowan	AFRL/MLPJ	937-255-3808x3148
Manufacturing Technology	Mr. Dennis Hager	AFRL/MLM	937-904-4347
Systems Support	Mr. Gary Kepple	AFRL/MLS	937-656-6054
AEF Technologies	Mr. Stan Strickland	AFRL/MLQ	850-283-6326

Materials & Processing Technology Thrusts

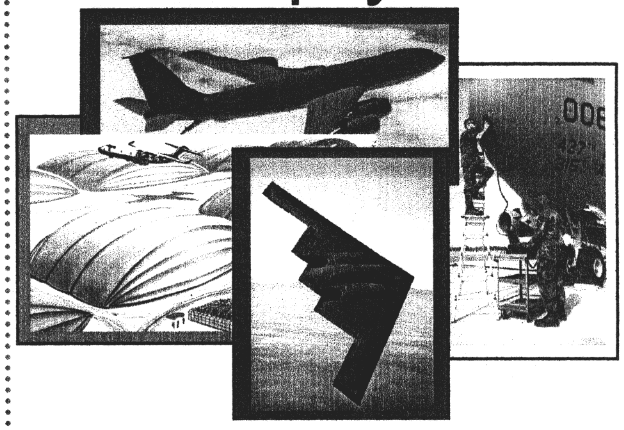
M&P for Structures and Propulsion



M&P for Sensors and Survivability



M&P for Sustainment and Deployment



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Core Sub-Thrusts

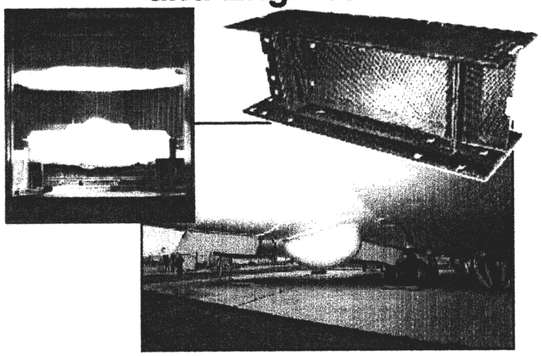
M&P for Structures and Propulsion	M&P for Sensors and Survivability	M&P for Sustainment and Deployment
• Metals • Composites • Ceramics	• Sensor Materials • Laser Hardened Materials • Polymers	• NDE • Systems Support • AEF Technologies • Coatings

Key Programs

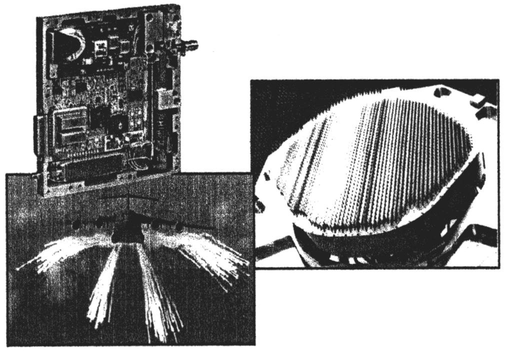
M&P for Structures and Propulsion	M&P for Sensors and Survivability	M&P for Sustainment and Deployment
• High Cycle Fatigue • Composites Affordability • Thermal Protection • IHPTET Materials • IHPRPT Materials	• IR Sensor Materials • Laser Protective Coatings & Devices • Power Generation • Polymeric Materials	• Aging Systems NDE • Agile Combat Support • Failure Analysis • Engine Life Extension • LO Maintainability

Manufacturing Technology Thrusts

ManTech for Structures and Engines



ManTech for Electronics and Sensors



ManTech for Sustainment

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Core Sub-Thrusts

- Metals Processing & Fabrication
- Composites Processing & Fabrication
- Manufacturing Modeling & Simulation
- Advanced Industrial Practices

- Electronics Fabrication & Assembly
- Electro-Optic Components
- Microwave Devices
- Radar Systems

- Repair/Refurbishment Processes
- Parts Obsolescence
- Nondestructive Evaluation

Key Programs

- Composites Affordability Initiative
- Metals Affordability Initiative
- Forging Supplier Initiative
- Casting Supplier Initiative
- Multi-functional Radomes
- Modeling & Simulation for Affordability
- Affordable Tool-Less Edge Fabrication
- Affordable Mfg. of Lo Coatings

- MEMs for IMUs
- LAIRCM (Affordable Missile Warning)
- Radar Subarray Systems
- Airborne Laser Window

- Lean Blade Repair
- Laser Shock Peening
- Electronic Parts Obsolescence
- Structural Repair of Aging Aircraft
- Lean Depot Repair
- Best Commercial Mfg. Practices
- Turbine Engine Life Extension
- Stretch Forming Simulation

MATERIALS AND PROCESSING TECHNOLOGIES

- **Current programs impacting structures and propulsion**
  - **High Temperature PMCs**
  - **Carbon-Carbon Materials**
  - **Thermal Management Materials**
  - **Processing for Dimensional Control**
  - **IHPTET**
  - **Life Prediction / High Cycle Fatigue**
  - **....**

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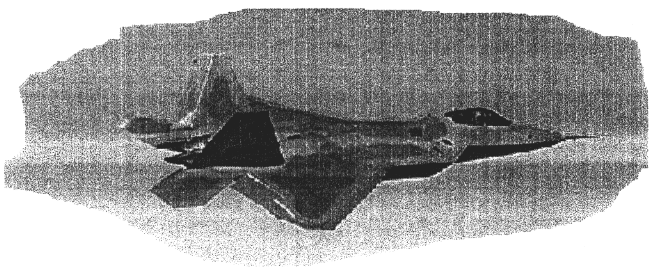
Technologies that may be available for demonstration

High Temperature PMCs

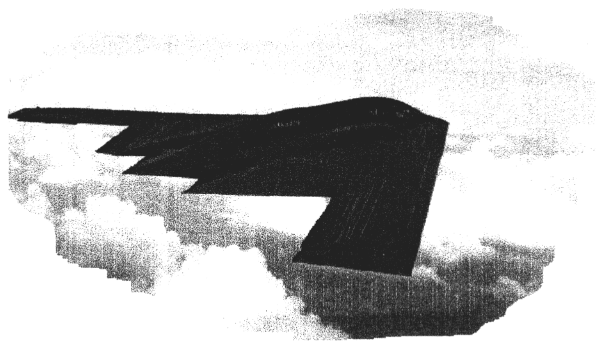
Goal: Sustained use 450°F & above; limited lifetime up to 700°F

- Environmental durability (Thermal oxidative and hygrothermal stability)
- Low-cost processing/material
- Environmentally friendly

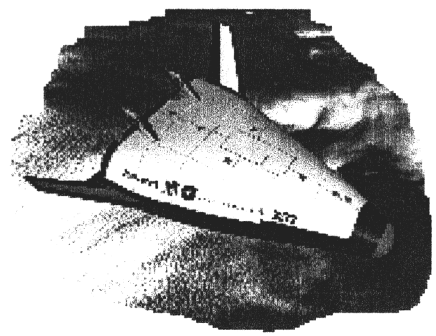
B-60



F-22, JSF: BMI matrix composite offers higher design allowables, lighter structure, inexpensive processing



B-2, F-117A, F119: High temperature organic matrix composites allow high temperature structure in engine and exhaust impingement applications



Hot internal structure reduces weight of thermal protection system, lighter engines

Thermal Management Materials
C-C Heat Exhanger

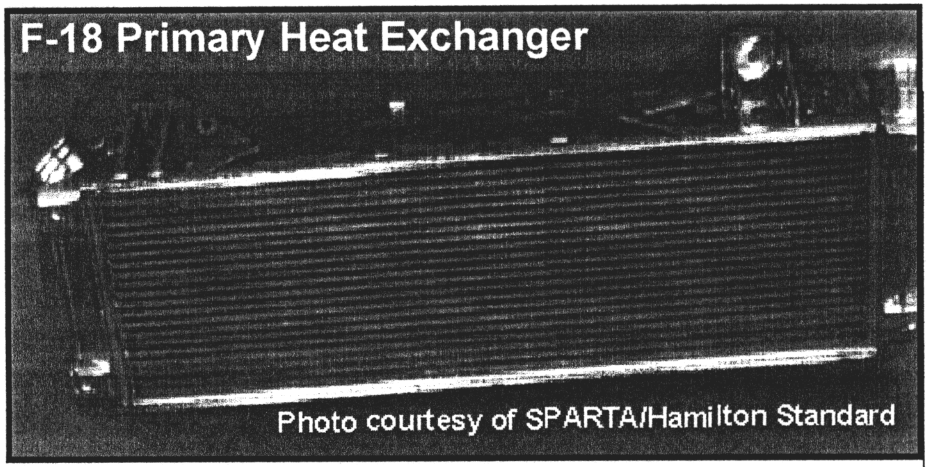

F-18 Primary Heat Exchanger

Photo courtesy of SPARTA/Hamilton Standard

13-61

OBJECTIVE

- Develop oxidation Resistant C-C for 1200F heat exchangers

TECHNICAL APPROACH

- Generate oxidation protection data for coatings and inhibitors
- Develop coating technique for a C-C HX core
- Demonstrate oxidation protection scheme for C-C primary HX
- Deliver material property data

BUSINESS DETAILS

- Contract Number(s): CA# F33615-99-2-5216
- Contractor(s): Honeywell International
- Start Date: Aug 1999 /37months
- Project Manager: Roland Watts AFRL/MLBC

e-mail: Roland.Watts@AFRL.AF.MIL

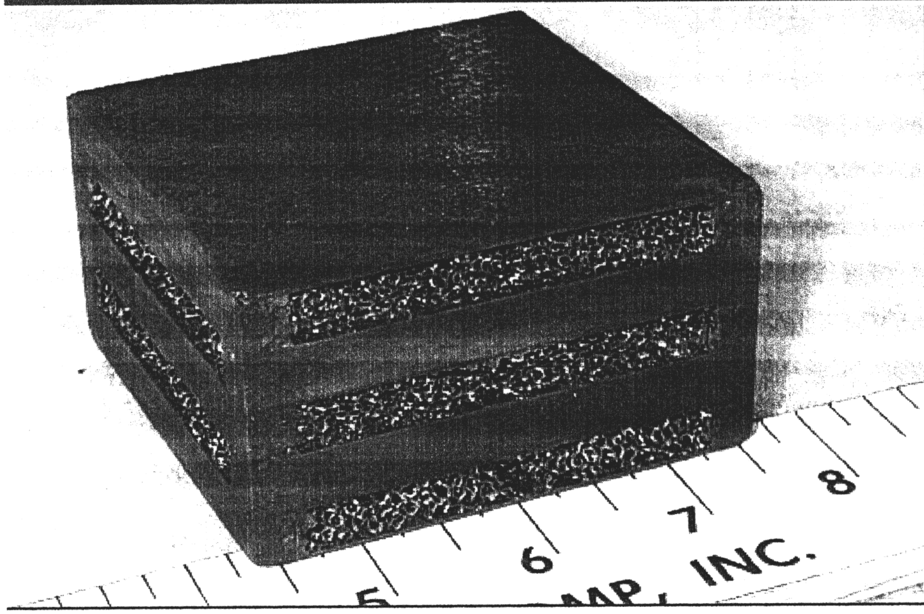
AF Funding:

FY00	FY01	FY02	FY03	FY04	**Total**
324	315	236			**875**

BENEFITS

- Provide extended life, lightweight, corrosion-resistant, very efficient Environmental Control System
- Extends time between failure by 2X
- Extend range due to 40% weight reduction and increase heat exchanger efficiency by 10%
- Extension of capabilities due improved/new electronics technology

Thermal Management Materials
Carbon Foam Heat Exchanger



B-62

OBJECTIVE

- Develop extremely light-weight, high conductivity composite heat exchangers

TECHNICAL APPROACH

- Optimize open HiK pore structure and plate joint attachment
- Generate performance data using sub-scale heat exchanger
- Use data to design and fabricate full size heat exchanger to decrease volume/increase cooling capacity

BUSINESS DETAILS

- Contractor(s): Allcomp, Inc.
  TBD
- Start Date: Oct 1999 /24 months
- Project Manager: POC: Tom Gilmour NAVAIR
  Roland Watts AFRL/MLBC

e-mail: Roland.Watts@AFRL.AF.MIL

	FY00	FY01	FY02	FY03	FY04	Total
Navy Funding:	300	300				**600**
Air Force Funding:				150	350	**500**
Industry Cost Share			TBD	TBD	TBD	

BENEFITS

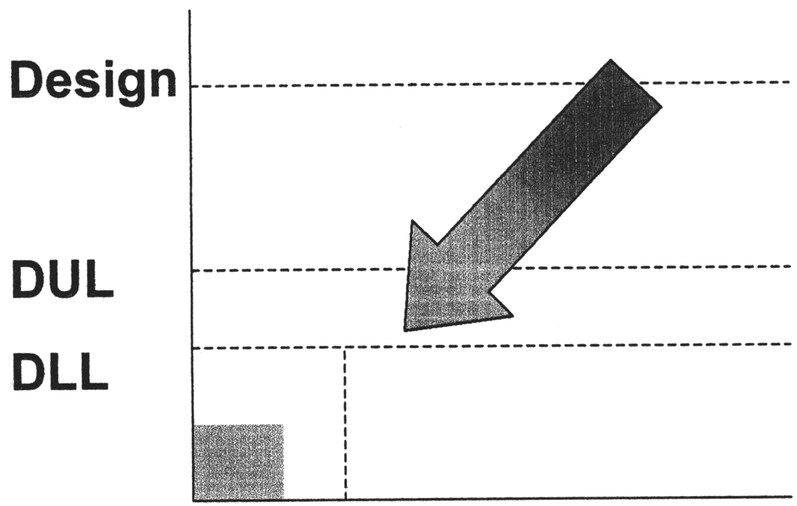
- Provide extended life, lightweight, corrosion-resistant, very efficient Environmental Control System
- Extends time between failure by at least 2X
- Extend range due to 70% weight reduction and
  increase heat exchanger efficiency by 25%
- Increase heat transfer coefficient, h by 5X

High Fidelity Analysis Tools

PMCs Currently Penalized through "Factors" in Design

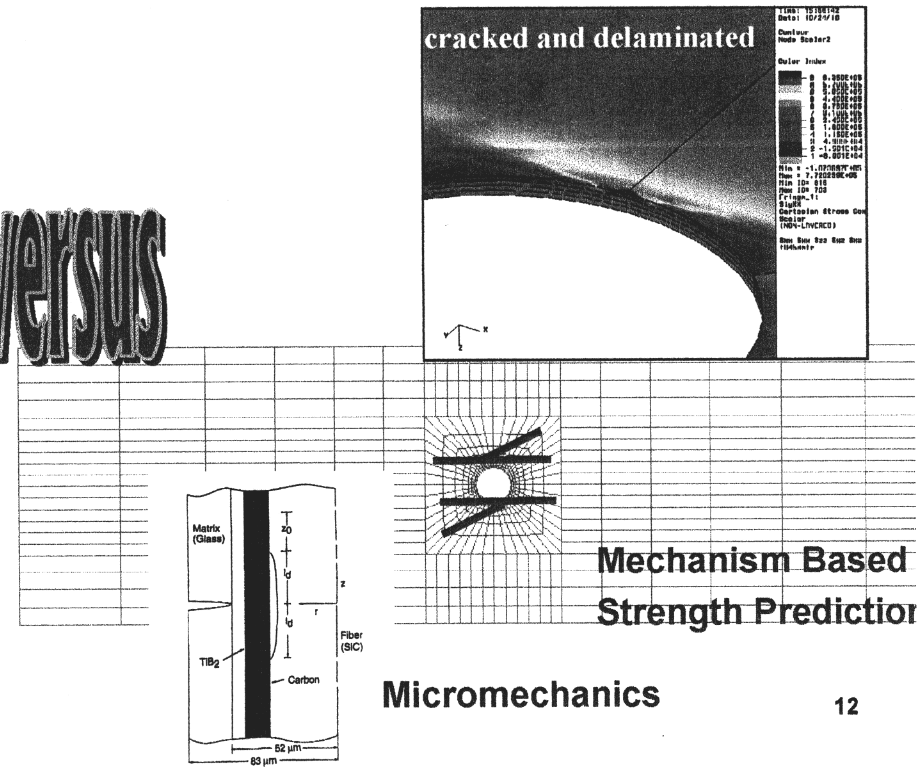
- True potential benefits not realized
- Lack of understanding, tools, failure criteria
- Design Limit Load: worst case, low probability

B-63



D = DUL * (Knockdowns ...hot/wet, open hole, ...)

versus



Mechanism Based Strength Prediction

Micromechanics

High Fidelity Analysis Tools

VISION: UNDERSTANDING = accurate failure prediction
= control of structural load paths
= "real" factors of safety
= minimal testing

3-D Stress and Fracture Analysis

3-D Failure Criteria

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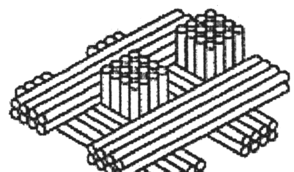
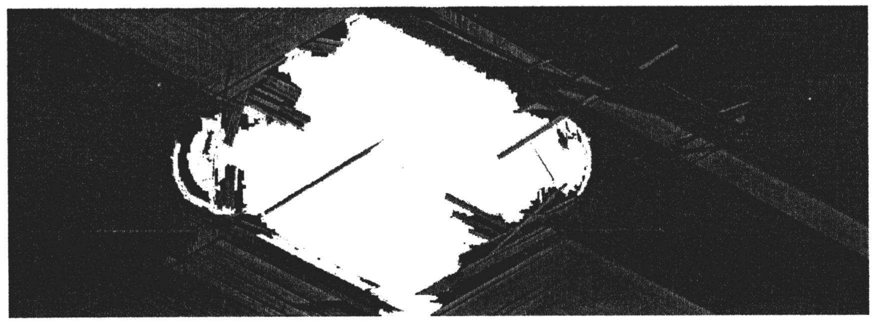
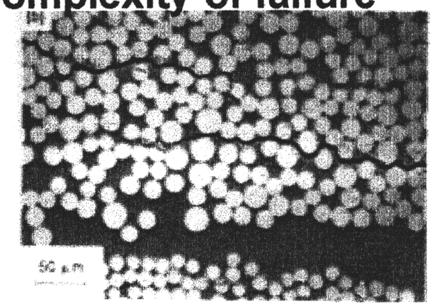


New material forms



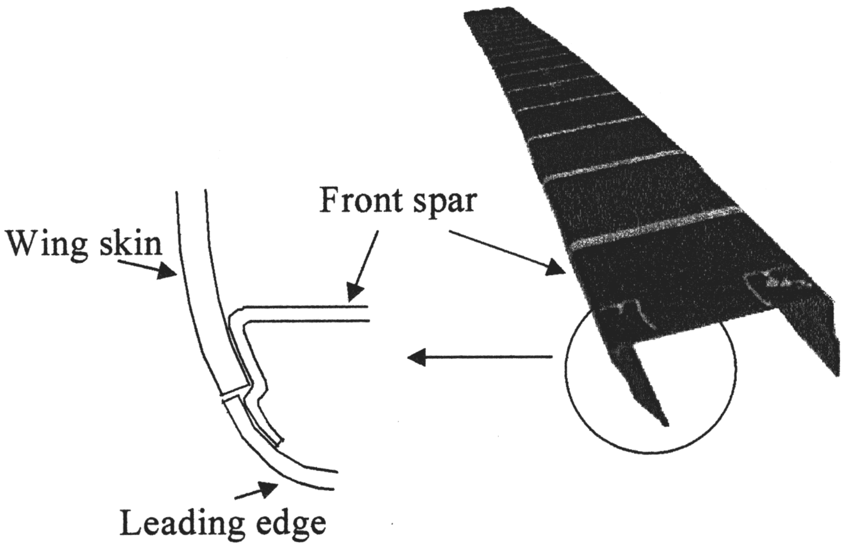
Bolted joint specimen shows complexity of failure



Micro-level damage

PRACTICE: EMPIRICISM = extensive testing
= weight
= cost
= time

Processing for Dimensional Control



B-65

OBJECTIVE

- Develop tools for the fabrication of composites with improved dimensional control

TECHNICAL APPROACH

- Establish the cost and performance benefits
- Predict spring-in of as-designed part via model
- Compensate tooling based on model predictions for spring-in
- 2-D, 3-D Model; Cost Analysis

BUSINESS DETAILS

- Contract Number(s): F33615-97-C-5006
- Contractors: Boeing
- Start Date: Nov 1997 – Nov 2001
- Project Managers: Roger Gerzeski, AFRL/MLBC

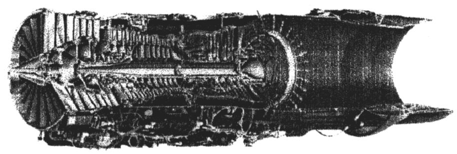
  e-mail: Roger.Gerzeski@AFRL.AF.MIL

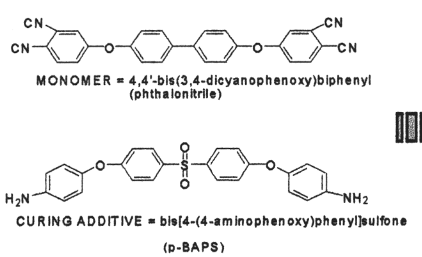
Air Force Funding:	PY	FY00	FY01	FY02	**Total**
	645	418	1352	6	**1421**

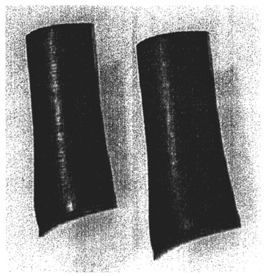
BENEFITS

- Reduced assembly costs for large, integrated structures
- Bonded/joined structures enabled
- Low cost through reduced shimming, tool rework
- Processing simulation abilities for reduced cost, lead times

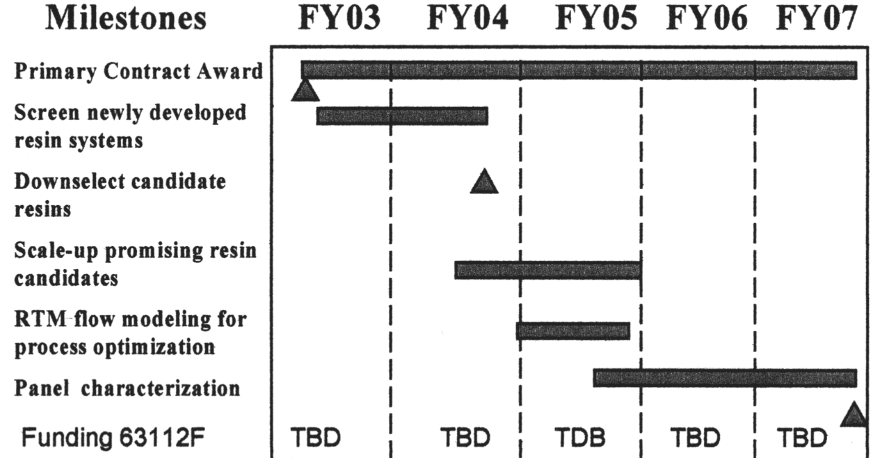
High Temperature Polymer Matrix Composites







Technology Investment Schedule **As of 8 Mar 01**



Description

- Allow commercial deployment of new, non-toxic, environmentally durable, low-cost fabrication resin systems for high temperature applications

Technology

- Develop polymers for composites used in turbine engine applications of 550-700°F
- Develop and demonstrate low-cost fabrication methods for high temperature polymer composites
- Enhance the hygrothermal stability of high temperature polymer matrix composites

Benefits to the War Fighter

- Reduced weight of fan section components, enabling improved thrust-to-weight ratios and greater mission capabilities
- Dramatically reduced costs of high temperature polymer matrix composite engine and airframe applications
- Improved environmental durability
- Decreased toxicity during manufacturing and repair

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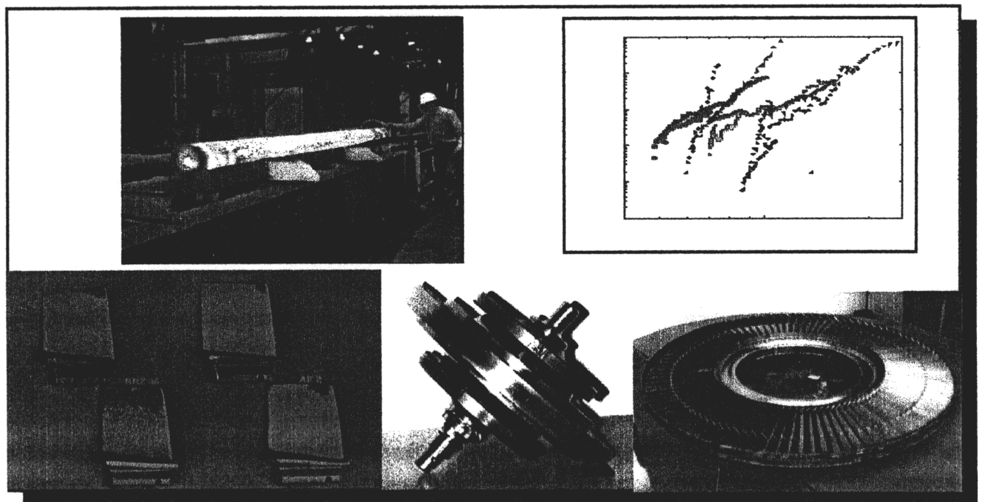
ADVANCED M&P FOR IHPTET

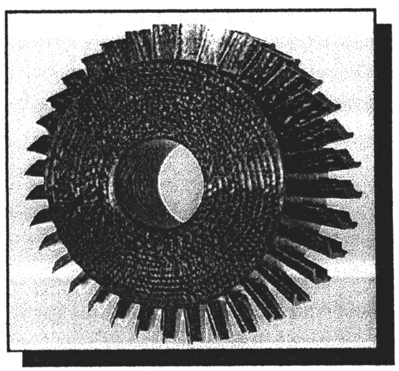
Research Areas

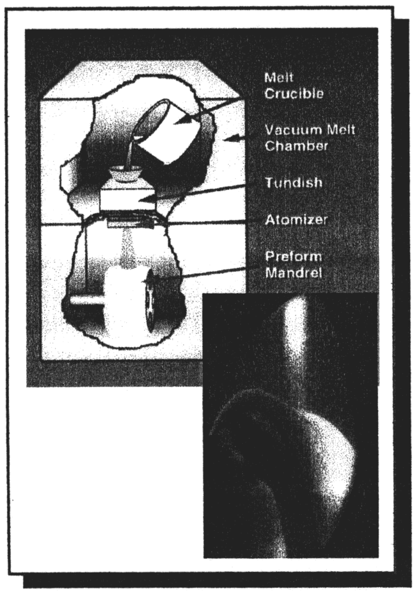
1996
γ TiAl
Adv. Intermetallics (Mo, Nb)
CMCs
Ti-MMCs
Bearing Materials
Fluids, Lubricants
Hi Temperature OMCs

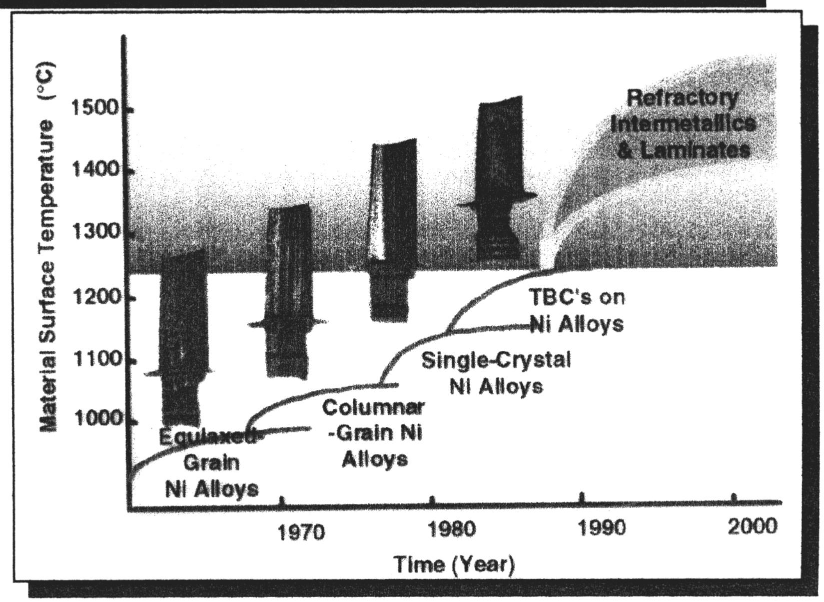
13-67

2000
γ TiAl for Fracture Critical Applications
Advanced Intermetallics (Mo, Nb)
Affordable Processing
HCF
2400°F CMCs
Hi Temperature OMCs









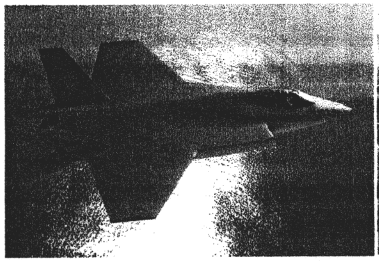
MANUFACTURING TECHNOLOGY

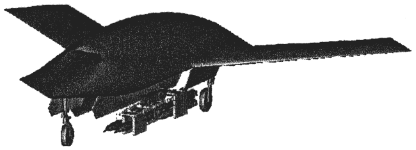
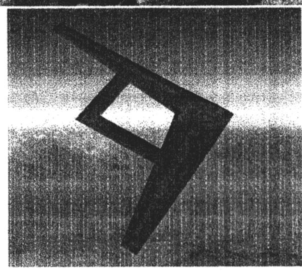
B-68

- **Current programs* impacting structures and propulsion**
  - Composites Affordability Initiative
  - Metals Affordability Initiative
  - Forging Supplier Initiative
  - Casting Supplier Initiative
  - Laser Shock Peening
  - Engine Rotor Life Extension

*TRL5/6 within ~5 years

COMPOSITES AFFORDABILITY INITIATIVE



B-69

Objective

- Provide technologies that will enable an order of magnitude reduction in acquisition costs of advanced composite structures

Approach

- National partnership - Government and industry
- Utilize revolutionary design / manufacturing concepts
- Couple technology development with transition demos

Deliverables

- Affordable design/manfuacturing/assembly technologies
- Supporting structural analysis and non destructive evaluation tools
- Cost model for composite airframe designers
- Validation of technologies, performance, affordability and ROI through transition demonstrations

Milestones

JSF phase 2 demos complete	FY01
Innovative M&P specifications complete	FY03
Full scale V-22 spindle demo complete	FY04
Full scale UCAV structural demo complete	FY04
Complete cost analysis tools validation	FY05

Contract Numbers: F33615-98-C-5103 through 06

Funding($K)	97-00	FY01	FY02	FY03	FY04	FY05
AF ML 7.8	16170	5000	5000	5000	5000	3500
AF ML 6.3	530	0	0	0	0	0
AF ML 6.2	1000	0	0	0	0	0
AF VA 6.3	2184	1988	944	2044	1524	0
AF VA 6.2	2751	0	0	0	0	0
Navy 7.8	22000	1075	2675	2100	850	2550
JSF Program	500	0	0	0	0	0
Industry	43362	8167	9450	9650	7450	9000
TOTAL	**88497**	**16230**	**18069**	**18794**	**14824**	**15050**

Customers

- Near Term - JSF, UCAV, V-22, F-22, SensorCraft
- Far Term - Rotorcraft, land, sea, and space systems

Benefits

- Significant improvements in composites affordability
- Increased system performance via increased composites useage
- Advanced aerospace industry state-of-the-art

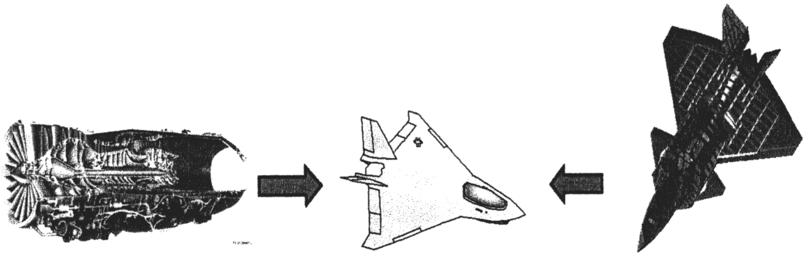
Implementation

- Near term: Phase 2 technology included in the JSF EMD proposals

Related Efforts

- Rotary Wing Structures Technology Demo - Army
- Knowledge & Processing Tools for Manufacturing of Affordable Composite Structures - Army

METALS AFFORDABILITY INITIATIVE



ENGINES
- •80% Metal Components
- •20-25% System Cost

AIRFRAME
- •67% Airframe Wt. Metal
- •33% System Cost

B-70

Objective: Address key drivers to recurring engine & airframe costs through affordable metal products

- Collaborative effort with industry
  - 25% industry high quality cost share
- Reduce metal component acquisition cost by 50%
  - Reduce time to market
  - Pervasive technology advancement

Technical Challenges:

- Efficient Manufacturing
- Collaborative Design
- Reduced Part Count
- Improved Yield
- Lower Cost Alloys
- Reduced Time to Market
- Reduced Inspection Steps
- Reduced Maint'nce Actions

CONTRACT BACKGROUND

Contract: F33615-99-3-5216/5215
Contractor: Pratt & Whitney
Start: July 99
Duration: 84 Months
Project Engineer: Kevin Spitzer

Gov't Funding Profile ($K)

	FY99	FY00	FY01	FY02	FY03	FY04
(7.8)	$1700		$3800	$2000	$3000	$4000
OTHER	$4850	$8515	$14215	$5160	$3120	$1375

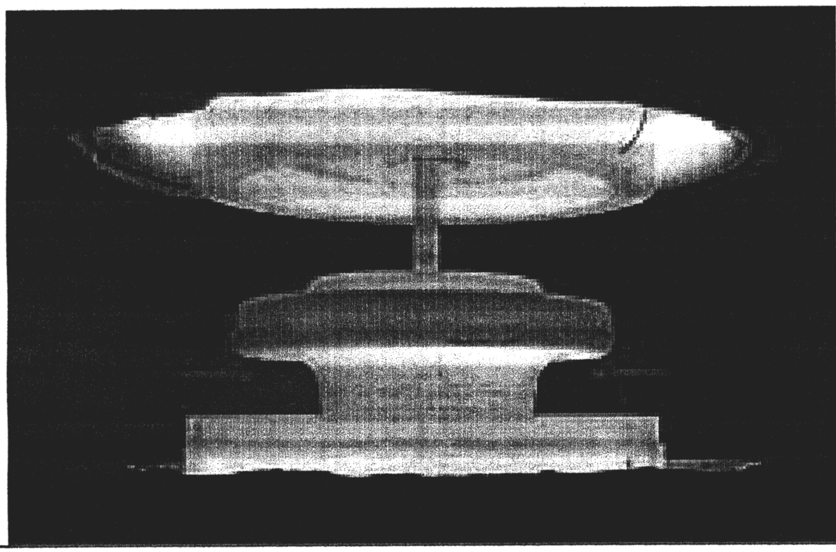
Payoffs

- Reduced Acquisition and Retrofit Costs
  - Threshold: 30%
  - Goal: 50%

- Initial Implementation in JSF
- Aircraft in production (F-22, F/A-18E/F, V-22)
- Mature aircraft (F-15, F-16, C-17, C-130, F/A-18 C/D)
- Unmanned Air Vehicles
- Space Applications

A Robust, Responsive Supplier Base for Defense and Commercial Metals Products

FORGING SUPPLIER INITIATIVE



B-71

OBJECTIVE

• Achieve a 35% to 40% cost reduction for current and future Air Force and Navy airframe and propulsion forged components by attacking affordability issues through the forging supply chain

APPROACH

• Use of value stream analysis to identify areas of opportunity
• Address shop floor, above the shop floor and business practice topics
• Extension of corporate lean activities (i.e: Navy, R&D base)
• Execution of plan with cost reduction demonstrations

DELIVERABLES:

• Implemented improved practices and processes
• Establishment of the "process of change" for transition

BUSINESS STRATEGY

• Contract Number: F33615-99-2-5303
• Contractor: Pratt & Whitney - West Palm Beach, FL
• Start Date: MAY 99 / 46 months
• Phase I: MAY 99 - MAY 00 / 12 months
• Project Engineer: Kevin Spitzer AFRL/MLMP
• Air Force Funding:

	FY99	FY00	FY01	FY02	FY03	TOTAL
AF ManTech	600	2000	3000	2000	600	8200
AF ManTech			150*	150*	50*	350*

*MLMR Transition to forgings simulations

• NAVY ManTech Funding & Participation (NCEMT)

CUSTOMERS

- Joint Strike Fighter (JSF) Airframe & Propulsion
- F-22 & F-119
- F/A-18E/F & F414

BENEFITS

- 35 to 40 percent reduction in cost of forged product
- Joint service coordinated activity attacking affordability within the forging sector

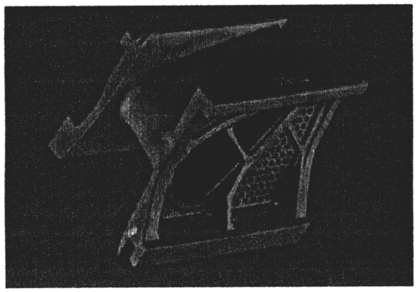
IMPLEMENTATION

Process improvements and cost reducing practices and processes will be implemented along the entire value stream for forged products, including Engine & Airframe OEM's, Forging Suppliers, and Raw Material Suppliers

RELATED EFFORTS

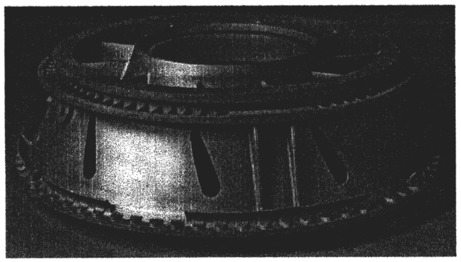
- AFRL/ML Metals Affordability Initiative
- AFRL/ML Engine Supplier Base Initiative

CASTING SUPPLIER INITIATIVE



Airfoils

Structural Castings



B-72

OBJECTIVE

Reduce the cost of components for man-rated gas turbine engines through cycle time reduction with an accompanying increase in quality brought about through the application of LEAN practices and principles.

APPROACH

- Vendor lead program teamed with industry and government to identify and attack shop floor and above the shop floor issues
- Define an infrastructure which is lean and promotes continuous improvement toward "world class"

DELIVERABLES

- Implemented LEAN Processes
- "Legacy" Document
- Self-sustaining Industry Forum for Continuous Improvement

CONTRACT BACKGROUND

Contract F33615-95-2-5555
Contractor: Howmet Whitehall MI
Start Sep 95
Duration 78 Months
Project Engineer Glenn Ormbrek

Funding

Prior	FY98	FY99	FY00	FY01	TOTAL
$4600	$4300	$4000	$3500	$3500	$20M

CUSTOMERS

Casting Sector Suppliers, OEMs, DoD

BENEFITS

- 50% improvement in quality as related to structural rework, and airfoil tolerance and single crystal scrap
- 25-50% improvement in cycle time as related to production cycle time, tooling procurement time, and new part design & process development time
- Build stable and cooperative relationships internally and externally, to implement cultural change in an terorganizational environment

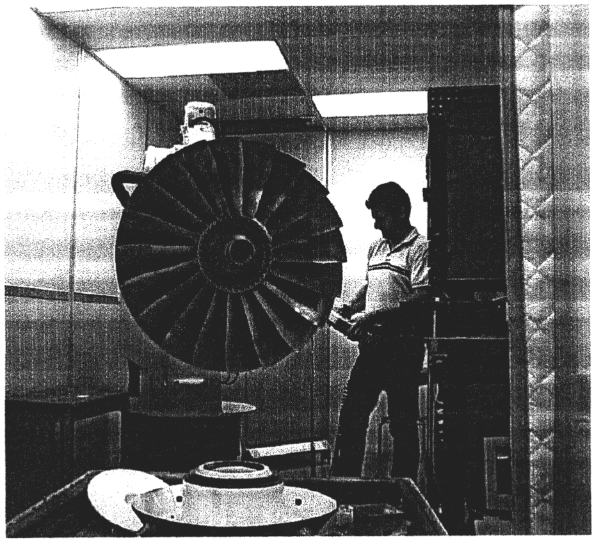
IMPLEMENTATION

Fielded Systems, F119/F-22, JSF

Related Efforts

Forging Supplier Initiative, Metals Affordability Initiative

MANUFACTURING TECHNOLOGY FOR AFFORDABLE LASER SHOCK PEENING



B-73

Objective: Mature LSP production process capability and implement an affordable production capable LSP manufacturing cell for applications to gas turbine engine blades and other fatigue critical components.

Technical Approach:

- Develop and implement advanced controls, monitors, and semi-automated processing sub-systems
- Design, fabricate, and implement an LSP Mfg. Cell (LSPMC)
- Demonstrate a production capable laser peening system at an aerospace user's facility
- Develop a commercial market for laser shock peening

Deliverables: Two production LSP systems. One installed and operated by LSPT. The second in production supporting the GE gas turbine engine production.

CONTRACT BACKGROUND

Business Strategy: Cost Share Effort with Air Force & Industry

Contract #: F33615-98-C-5150

Contractor Team: LSP Technologies (Lead)
General Electric, Pratt & Whitney
Commercial Users

Start Date/ Duration: Aug 98 48 Mo

Project Engineer: D. W. See AFRL/MLMP

Funding Profile:	FY98	FY99	FY00	FY01	FY02	Total
(MT) ($ K)	350	1350	1750	1600		5050
(LSPT) ($ K)	50	365	265	60		740

Customers:

- First Level: LSP Technologies , GE Aircraft Engines, Pratt & Whitney, and selected application partners TBD
- Second Level: F101, F110, F119, etc.

Benefits:

- Reduced Laser Shock Peening costs by 50% to 75% over current baseline costs
- Increased throughput by six to nine times over current baseline
- Increased leading edge damage tolerance by 15 X for critical gas turbine blades
  - Increase engine durability
  - Reduce maintenance costs

Implementation:

- LSPMC implementation at LSP Technologies
- Advanced Controls and monitors implemented at GEAE

MANUFACTURING TECHNOLOGY FOR ENGINE ROTOR LIFE EXTENSION

OBJECTIVES

Extend the operational lives of critical turbine engine components without increasing risk.

APPROACH

Develop and implement an affordable prototype maintenance system that reduces overhaul time, cost, and extends the useful life of critical turbine engine components.

- Advance inspection techniques for internal & surface defects
- Component preparation processes
- Surface treatment measurement/credit for residual stresses
- Data management/prognostics
- Repair/Refurbishment processes

DELIVERABLES

-Validated, Life management approach for turbine engines

-Prototype system implemented at OC-ALC

Contract Number: TBD

Prime Contractor/Location: TBD

Start Date/Duration: Sep 01, 30/54 Mos.

Program Manager: Jim Morgan, AFRL/MLMP

Funding($M)	FY01	FY02	FY03	FY04	FY05	TOTAL
AF ManTech	.200	2.50	5.00	5.00	2.30	15.0

•CUSTOMER(s)

-ACC (primary) for F100, F101, F110, F119 engines

•BENEFITS

Achieve major reduction in engine component replacement costs: 50% reduction between FY2005-2010

-Reduce inspection time by ~50%

-Reduce the risk of catastrophic failures

-$675M in potential savings in the 2005-2010 timeframe

•IMPLEMENTATION

-OC-ALC

•RELATED EFFORTS

-Multiple AFRL ERLE efforts (6.2, 6.3)

QSP Challenges

- **Structural Weight Fraction: WEIGHT**
  - High specific stiffness/strength
  - Multifunctionality
  - Tailorability
- **M2.0 – 2.4**
  - High Temperature (~400- 600F)
  - Long term durability at temp
    - HSR data…
    - Insulating properties to prevent aero heating raising fuel temp

    Multi-material solutions/integration
  - Fatigue resistance
  - Multifunctional
  - Bonding (outer skin smoothness)

B-75

QSP Challenges

- Design Practice Changes
  - Full utilization/exploitation of materials (composites)
  - 'ASIP' philosophy
- Manufacturing Issues
- Aeroelasticity Issues
- Probabilistic Design Requirements

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Air Vehicle Directorate
Structures Division

B-77

David M. Pratt, Ph.D.
Acting Technical Advisor
Structures Division

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Structures Division Mission

AIR VEHICLES DIRECTORATE

Plans, directs, manages, and performs basic research, exploratory development, and advanced development in air vehicle **structural design, structural technology integration, analytical structural mechanics, structural dynamics, sustainment, and extreme combined environment structures** to solve critical structural problems on fixed-wing aerospace vehicles. Supports the Air Vehicles Directorate's integrating concepts of aircraft sustainment, uninhabited air vehicles, and future strike/space operating vehicles. Transitions technology results and products to major Air Force commands, other government organizations and industry through in-house and contracted efforts, consultation to System Program Offices, Air Logistics Centers, and other AFRL Directorates, and through participation in professional organizations. Provides technical advice and support to other DoD organizations and government agencies.

Briefing (Dis)organization

AIR VEHICLES DIRECTORATE

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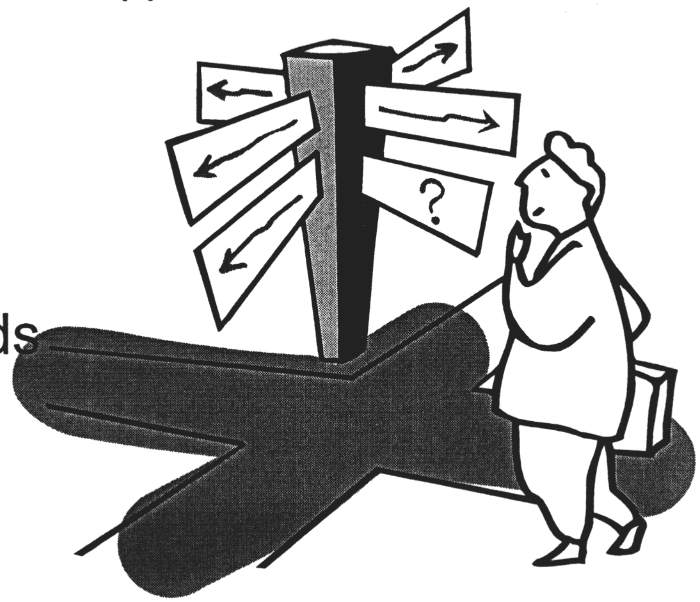
- Questions:
  - How would a Mach number range (2.0-2.4) impact new requirements?
  - How would you demonstrate using these materials and designs and what would be the maturity level required to do this?
  - How would design practices need to change if current materials are used?
  - What are the manufacturing issues?
  - What are the aeroelasticity issues for this type of vehicle?
  - What is needed to do a probabilistic design criteria approach?

- Issues – VAS slant
  - Embedded engine & aft decks
  - Light weight structures
  - Design/analysis – probabilistic methods
  - Aeroelasticity
  - Mission adaptable structure



Embedded engine & aft decks

B-80

EXHAUST WASHED THERMAL STRUCTURES

AIR VEHICLES DIRECTORATE

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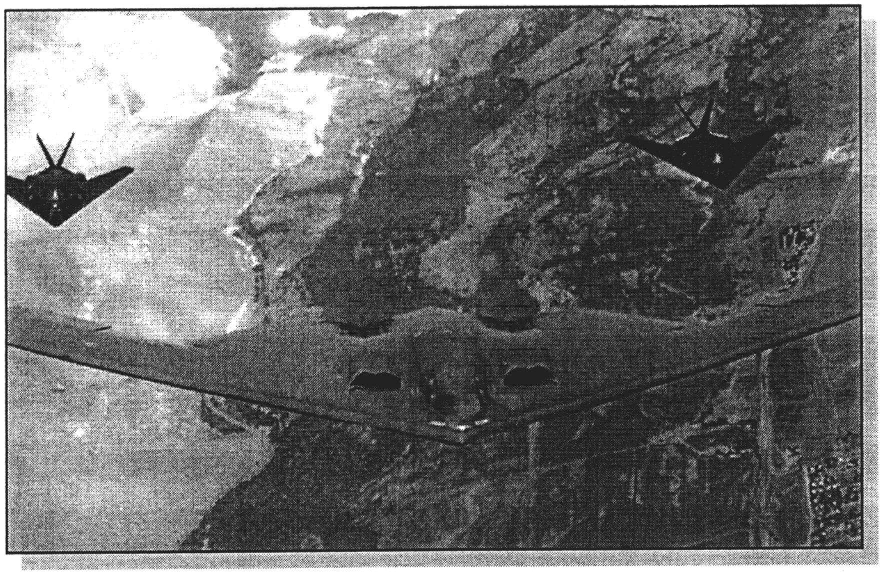


DESCRIPTION

Develop and Demonstrate Structurally Integrated Nozzles & Exhaust Washed Structures capable of operating in extreme environments

TECHNICAL CHALLENGES

- **Durability in thermoacoustic environment**
- **Structurally integrated airframe nozzles**
- **Concept fabricability**
- **Supportability/Maintainability**

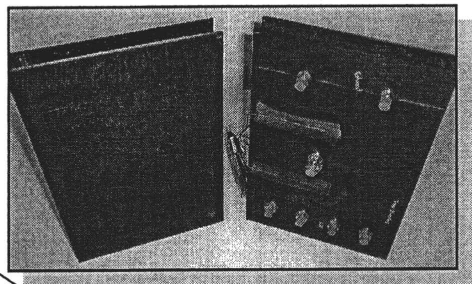
RELEVANCE

- **Reduce Structural Manufacturing Costs**
- **Reduce Structural O&S Costs**
- **Reduce Structural Weight**

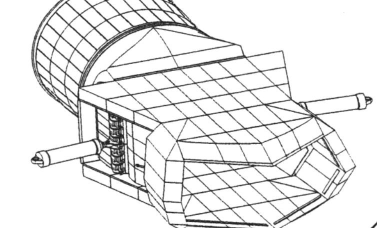
EXHAUST WASHED THERMAL STRUCTURES

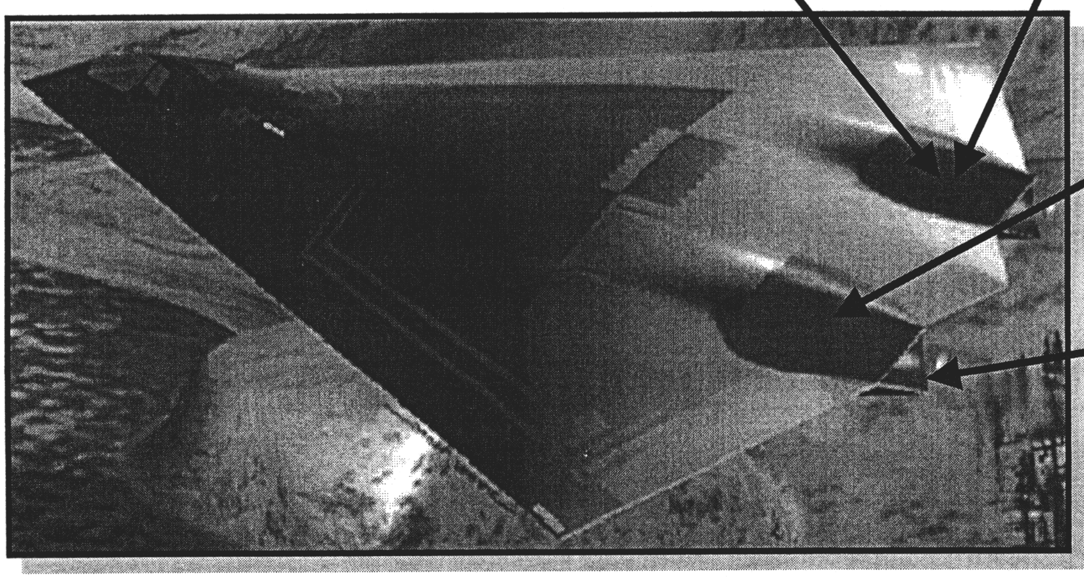
AIR VEHICLES DIRECTORATE

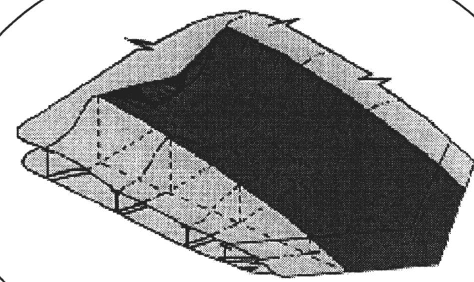
EXHAUST WASHED STRUCTURES



Develop, Fabricate and Test Highly Survivable Structurally Integrated Exhaust System Designs







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CASRL

FACILITIES

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CEAC

- 174 dB OASPL
- 50-500 Hz Flat Spectrum
- 50 Btu/ ft^2-sec
- 4'x10' Acoustic only
- 4'x4' Combined Thermal/Acoustic

SEF

- 174 dB OASPL
- 50-500 Hz Flat Spectrum
- 70 Btu/ ft^2-sec
- 12"x18" Combined Thermal/Acoustic

B-84

Combined Environment

- Variable Test Configurations
- Computer Controlled

Mechanical Load

Radiant Heating

Quartz Lamps – 114 W/cm2 (100 BTU/FT2S)

Graphite Heaters – 340 W/cm2 (300 BTU/FT2S)

Vortek Arc Lamp – 2270 W/cm2

(2000 BTU/FT2S)(Small Area)

Active Cooling (*Gases* - Nitrogen, Hydrogen, Helium, Argon, Air; *Liquids* - Water, Ethylene Glycol,JP-7, JP-8 Fuel, Nitrogen_

FUTURE CAPABILITIES

- 174 dB OASPL
- 50-500 Hz Flat Spectrum
- 70 Btu/ ft^2-sec
- 10'x10'Combined Thermal/ Acoustic/ Mechanical

Consolidated Aerospace Structures Research Laboratory (CASRL)

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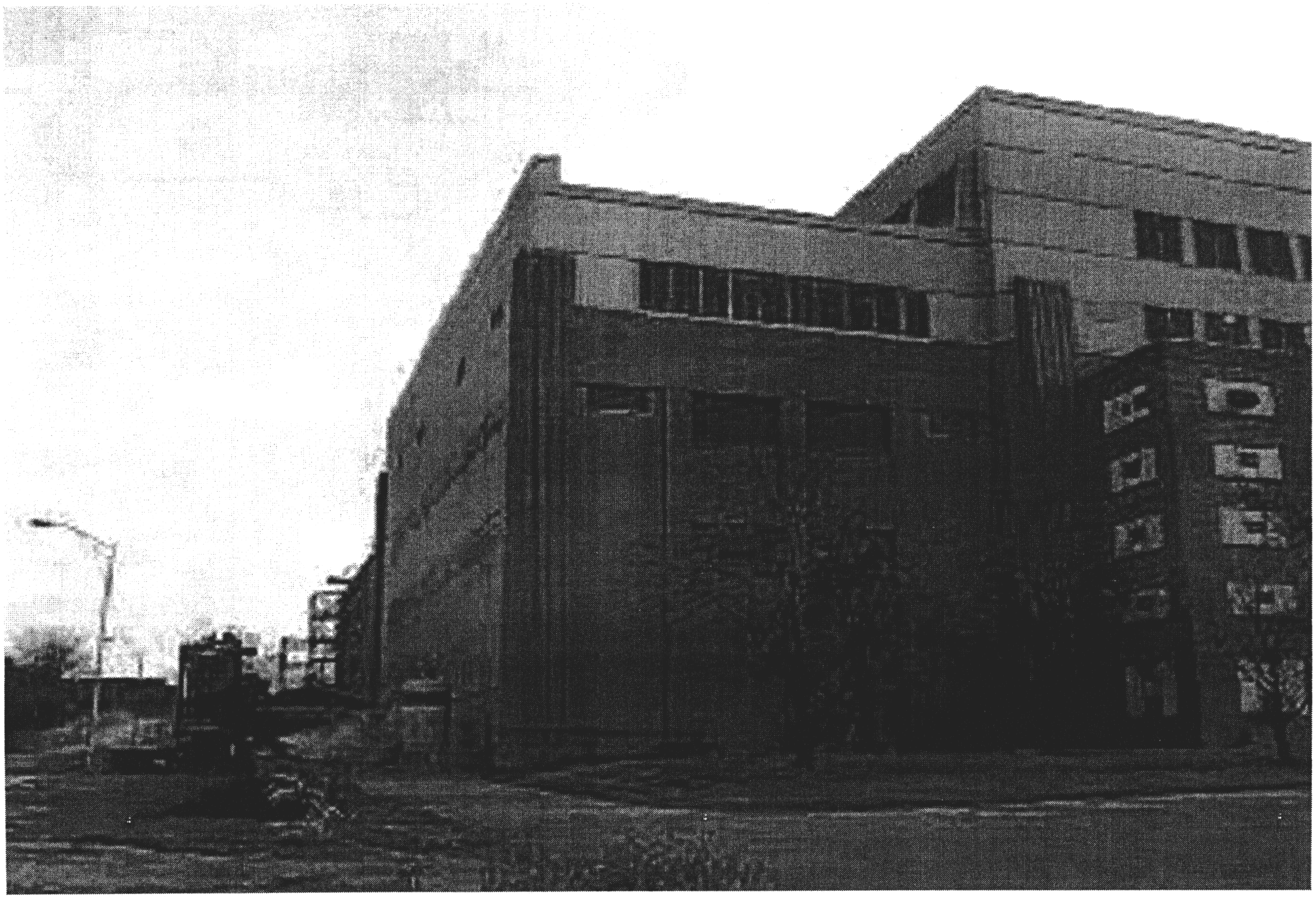

Light weight structures

13-86

Advanced Lightweight Aircraft Structures Program

AIR VEHICLES DIRECTORATE

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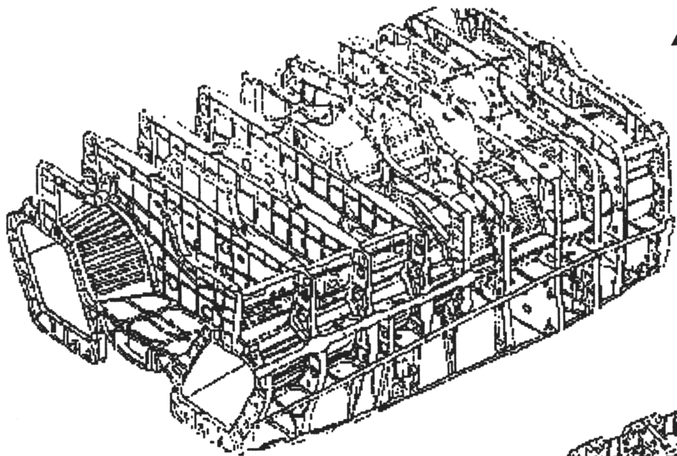
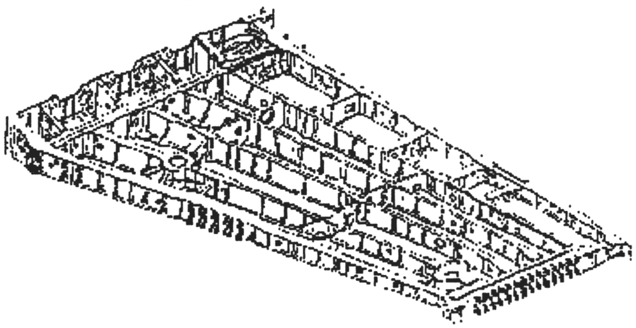
Sponsored By Joint Advanced Strike Technology (JAST) 1995-1998

Study Program to Demonstrate Cost/Weight Benefits Achievable Through Unitization

ALAFS BASELINE

F/A - 18 E/F Center Fuselage and Wing





Early Focus of Program was on Greater Application of Advanced Composites

As design matured emphasis on metals was increased

ALAFS Preferred Structural Concept

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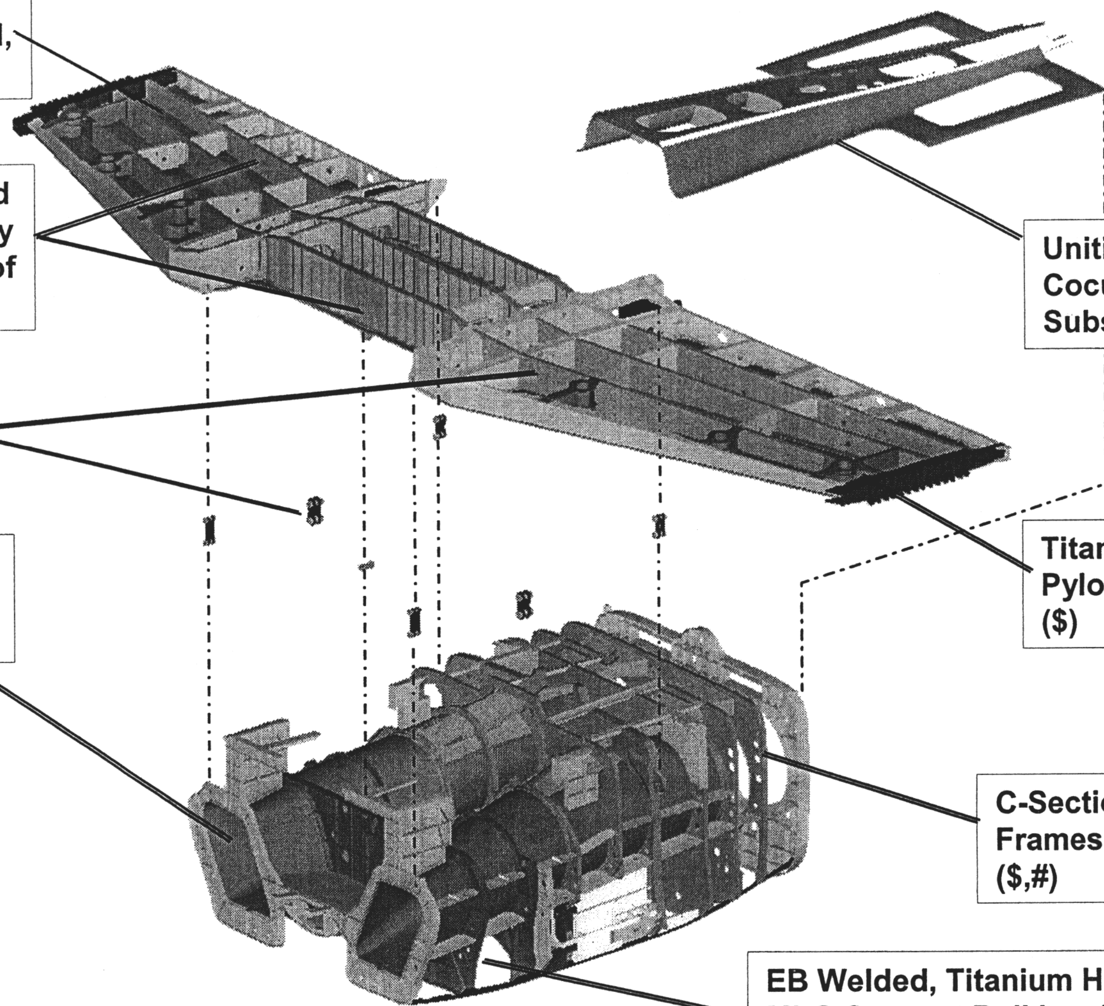

- RTM Composites
- Fiber Placed/Steered
- HSM Aluminum
- Titanium HIP Casting
- Aluminum Sh Metal
- Titanium Machining

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ALAFS Risk Technology - Alternatives

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Technology	Fallback Design	Cost Impact*	Weight Impact*
Syncore Sandwich	Monolithic skins	$ 50,000	77
Postbuckled C/E	Increased thickness in composites	$ 15,000	49
Fiber Placement & Steering	Hand collation	$ 100,000	0
HIP Casting	Increased part & fastener count. Assume HIP Cast bulkheads could be replaced with Ti forgings at equivalent weight. Deletion of HIP Castings would prevent MLG Sidebrace Integration to Y491 BH (+47 lb ftg/assy, -8 bulkhead).	$ 150,000	39
Ti Weldments	Machined forgings	$ 150,000	0
Hybrid Laminates	Bolted aluminum spars, increased ballistic foam. Deleting glass from the laminate would increase the stiffness enabling the duct to have a reduced thickness. In addition, deletion of the glass will lower the density of the laminate.	$ 30,000	57
3-D Inserts	Bolted metal fittings/parts	$ 10,000	19
RTM	Bolted metal parts, Ti spars	$ 25,000	150
C/E Unitization	Increased part & fastener count	$ 20,000	13
Cobonding	Increased part & fastener count, mechanical fastening	$ 20,000	5
Integrated Dimensional Mgmt	Rework on assembly, more shimming	$ 50,000	10

<u>"TOTAL FAILURE" GIVES BACK</u>	***<u>$620K</u>***	***<u>419#</u>***
ALAFS DESIGN BENEFITS	*$1137K*	*924#*

Composites Affordability Initiative

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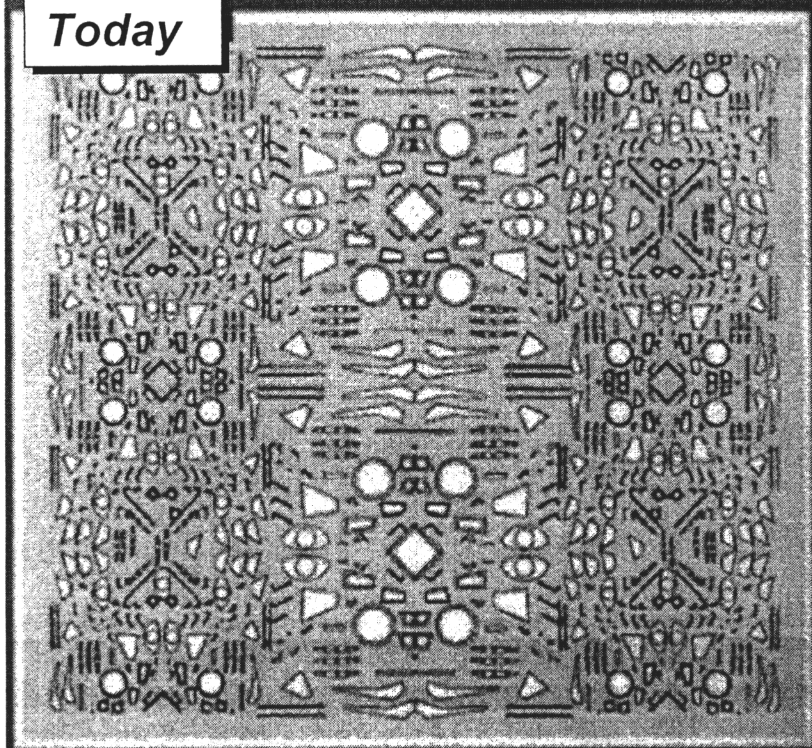
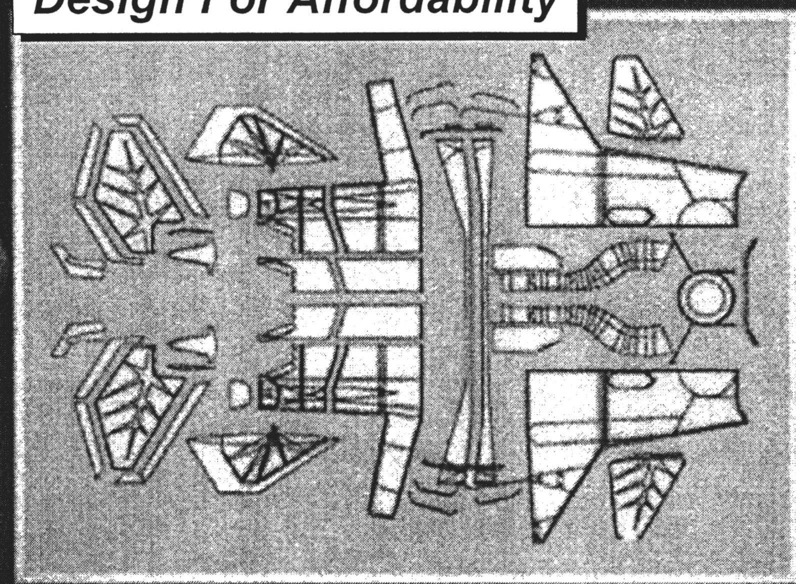
Today



- 11,000 Metal Components
- 600 Composite Components
- 135,000 Fasteners

Design For Affordability



- 450 Metal Components
- 200 Composite Components
- 6,000 Fasteners

- *Reduce Part Count*
- *Improve Producibility*
- *Dramatically Reduce Assembly Costs*

BOEING LOCKHEED MARTIN NORTHROP GRUMMAN

Ultra light weight structures program

Paradigm shift – there are NO boundaries between structural design, manufacturing technologies and materials

- Optimization of materials
- Bio-inspired concepts
- Reliability based design

Design/analysis - probabilistic methods

Design practice

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TODAY

- AML (Adaptive Modeling Language) – Engineering Framework for Collaborative Design
- ASTROS (Automated Structural Optimization System) – Preliminary design
- MDICE (Multi-Disciplinary Computing Environment)– Engineering Framework for High Fidelity Aero-Structures

REQUIRED

- AML
  - Higher Fidelity Interactions
  - Cost Models
  - Web Based Design
- ASTROS
  - Higher Fidelity Aero Codes
  - Commercialization
- MDICE
  - Additional Aero Codes
  - Controls & Thermo Module
  - Reduced Order Models

Probabilistic Methods

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TODAY

- Reliability based design
  - Estimates
  - Low fidelity
- Probabilistic/uncertainty
  - Huge
  - 3D
  - Use of Monte Carlo
  - Impact of prob dist for aero response of panels LCO

REQUIRED

- Reliability based design of aeroelastic systems
  - Identification of reliability metrics and parameter
  - EX: Tips deflection
    - Failure criteria - not to exceed
    - Sensitive parameters ➔Likelihood of failure
- Probabilistic/uncertainty
  - Stochastic FEM – Mid Fidelity
  - Fluid/structure interaction

MDT

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Multi-Disciplinary Technologies Center

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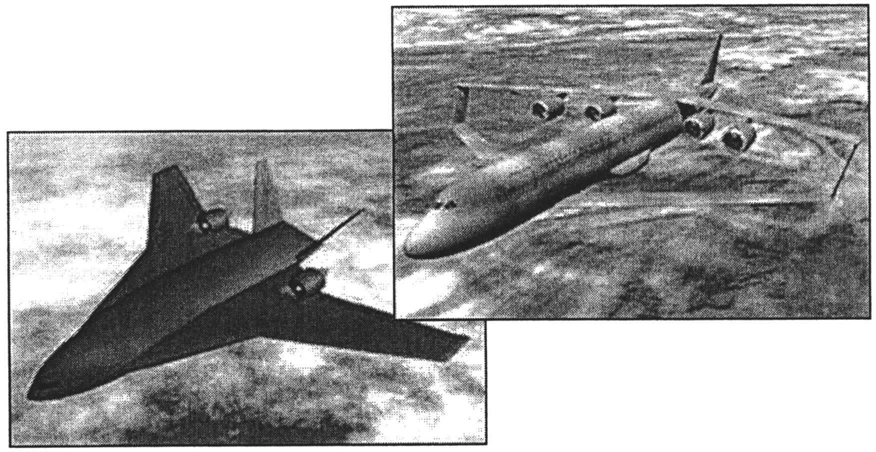
Objective: Lead the development and innovation mulitdisciplinary design and analysis technologies, methodologies and processes that enable revolutionary aerospace vehicle capabilities for the warfighter



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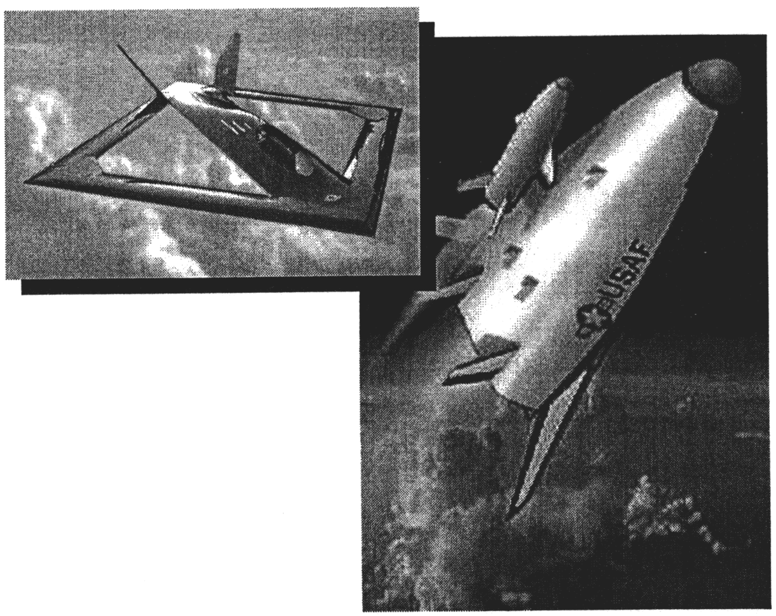


Areas of expertise:

- Multidisciplinary methods for design and analysis
- **Design processes**
- **Uncertainty analysis**
- **Innovative A/V concepts**
- **Reduced order modeling**
- Cost modeling
- **Optimization**

Aeroelasticity

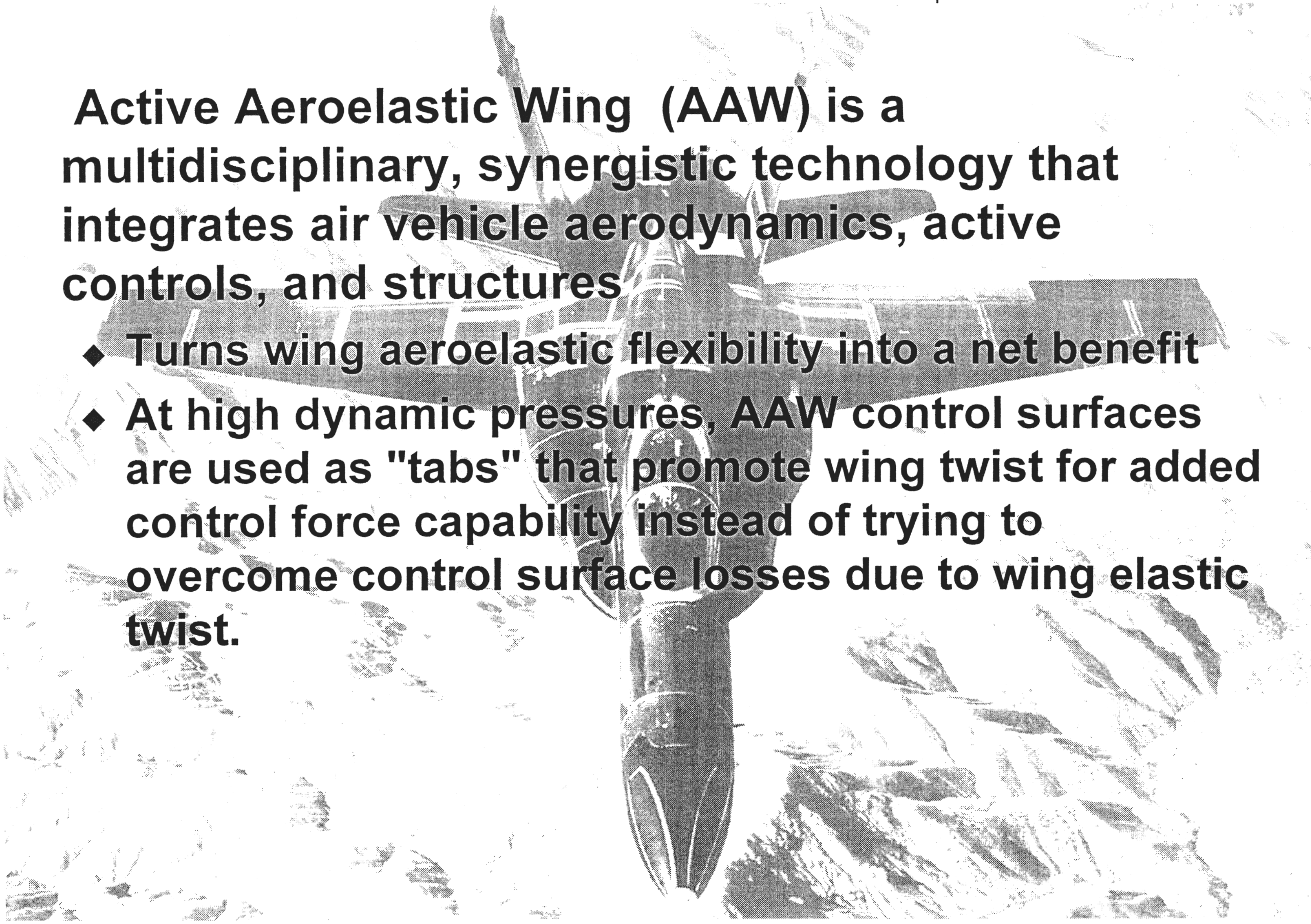
Aeroelasticity

- Aeroelasticity issues, but no show stoppers if the stiffness is adequate
- Instabilities → Active control
- Need to assess
  - Aeroelastic tailoring – passive
  - Active controls
  - Adaptive structures – AAW, HiLDA, …

Mission adaptable structures

Active Aeroelastic Wing

AIR VEHICLES DIRECTORATE



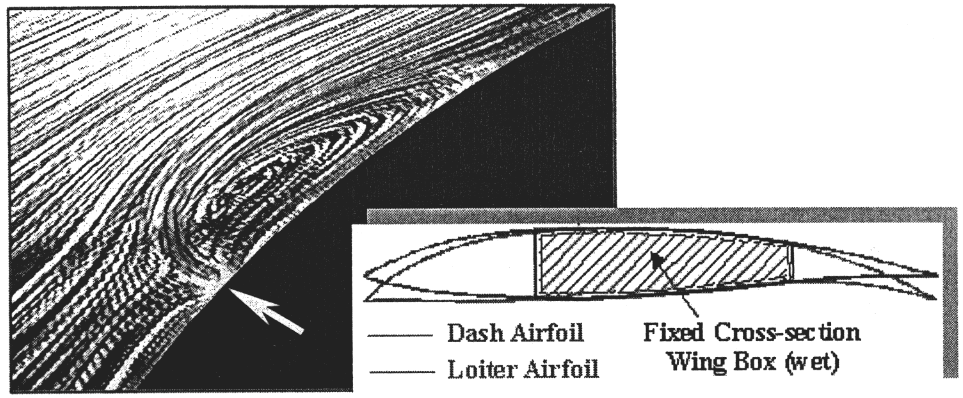
Active Aeroelastic Wing (AAW) is a multidisciplinary, synergistic technology that integrates air vehicle aerodynamics, active controls, and structures

- **Turns wing aeroelastic flexibility into a net benefit**
- **At high dynamic pressures, AAW control surfaces are used as "tabs" that promote wing twist for added control force capability instead of trying to overcome control surface losses due to wing elastic twist.**

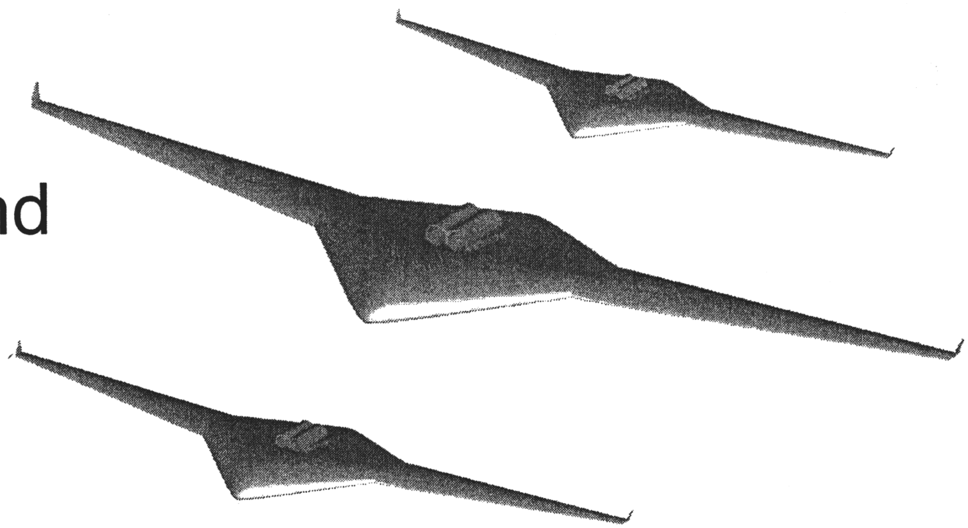
B-100

High L/D Active (HiLDA) Wing

AIR VEHICLES DIRECTORATE



- Apply AAW, adaptive structures and active flow control to a Sensorcraft wing design for load reduction and improved L/D.



B-101

Adaptive structures

AIR VEHICLES DIRECTORATE

- Some additional ideas
  - Leading edge
  - Inlets

13-102

- Adaptive structures- Maj Brian Sanders

Backups

B-103

COMBINED ENVIRONMENT EXPERIMENTAL CAPABILITIES

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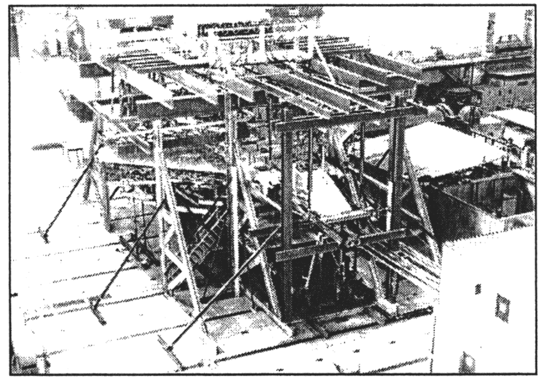


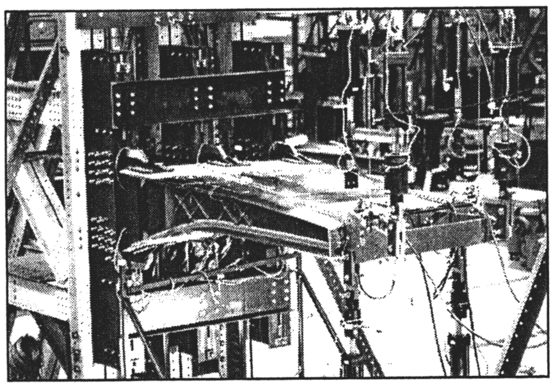
B-104

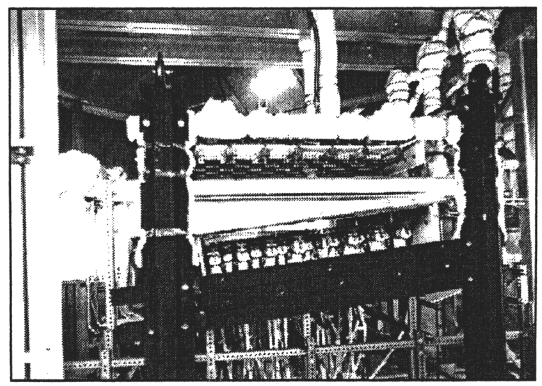
EXPERIMENTAL CAPABILITIES

Variable Test Configurations
Computer Controlled
- Mechanical Load
- Radiant Heating
  - Quartz Lamps – 114 W/cm^2 (100 BTU/FT^{2}S)
  - Graphite Heaters – 340 W/cm^2 (300 BTU/FT^{2}S)
  - Vortek Arc Lamp – 2270 W/cm^2 (2000 BTU/FT^{2}S)(Small Area)
- Active Cooling
  - Gases - Nitrogen, Hydrogen Helium, Argon, Air
  - Liquids - Water, Ethylene Glycol JP-7, JP-8 Fuel, Nitrogen

Data Acquisition
- 512 Data Channels Per Test
- Real Time Data Processing and Display

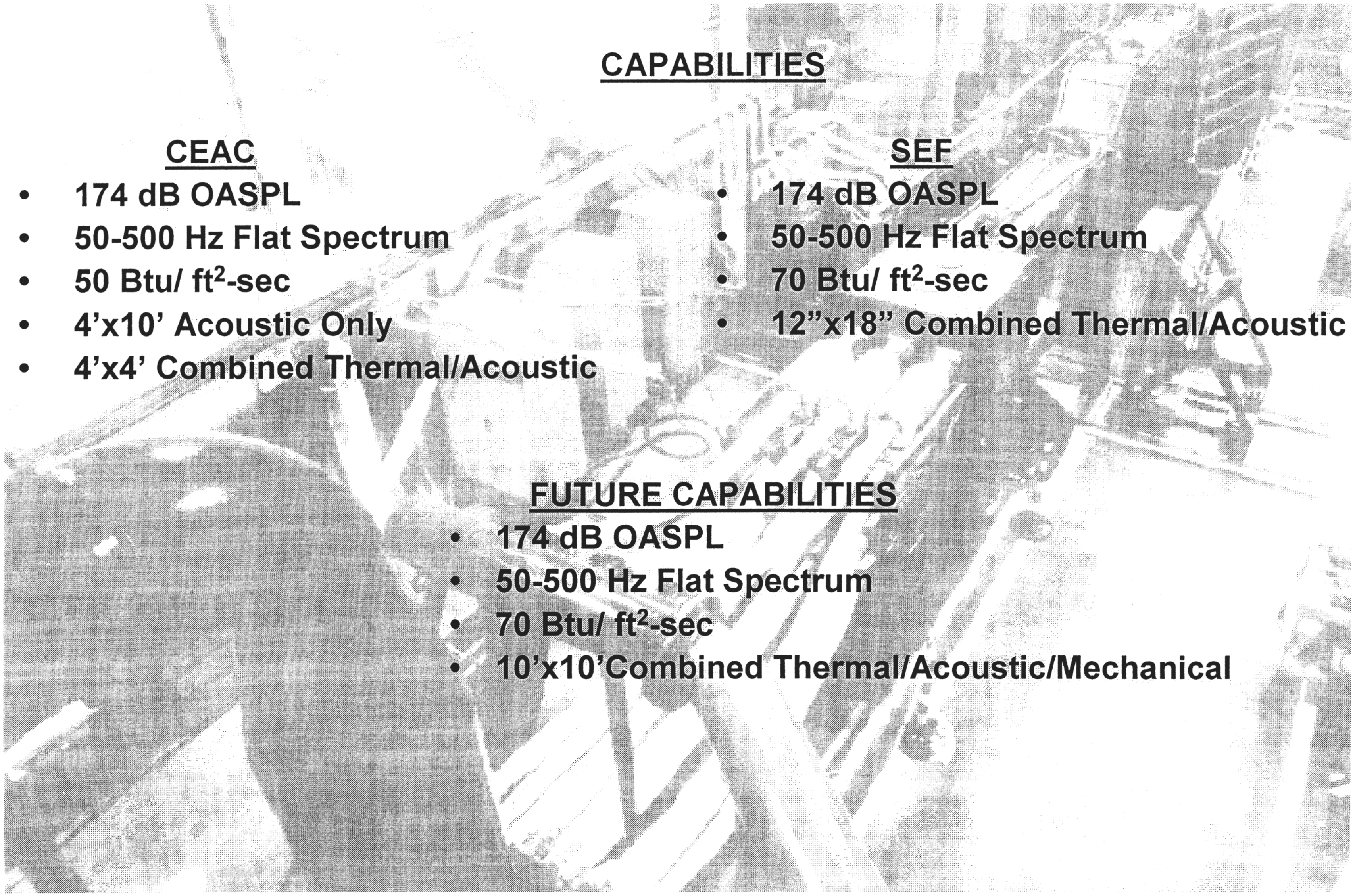
Instrumentation
- Room and Elevated Temperature Strain Temperature, Mechanical Load, Flow Pressure, Deflection





THERMAL/ACOUSTIC FACILITIES

AIR VEHICLES DIRECTORATE



CAPABILITIES

CEAC

- 174 dB OASPL
- 50-500 Hz Flat Spectrum
- 50 Btu/ ft^2-sec
- 4'x10' Acoustic Only
- 4'x4' Combined Thermal/Acoustic

SEF

- 174 dB OASPL
- 50-500 Hz Flat Spectrum
- 70 Btu/ ft^2-sec
- 12"x18" Combined Thermal/Acoustic

FUTURE CAPABILITIES

- 174 dB OASPL
- 50-500 Hz Flat Spectrum
- 70 Btu/ ft^2-sec
- 10'x10'Combined Thermal/Acoustic/Mechanical

B-105

AML Importance

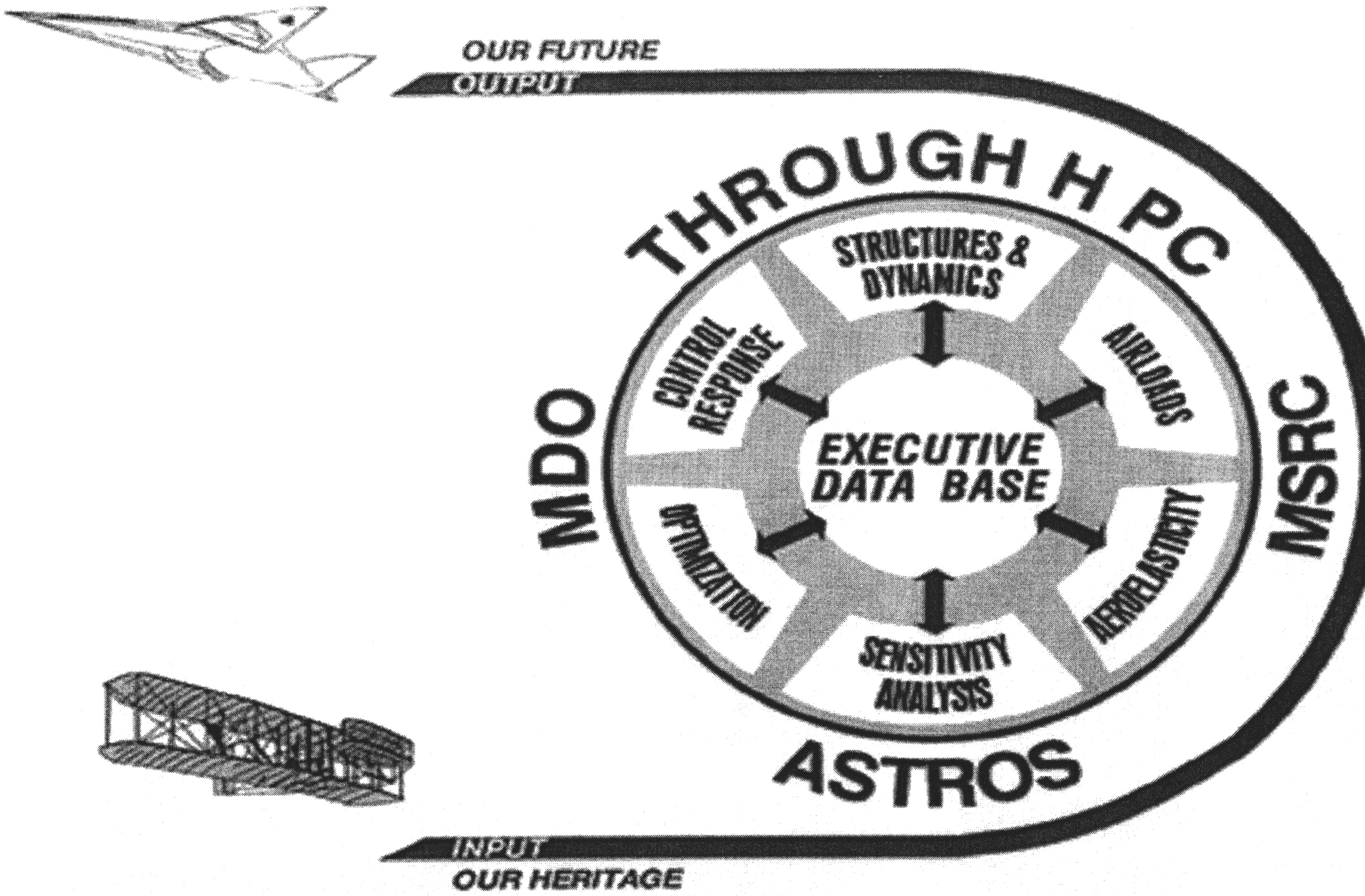
B-106

- AML provides an object oriented engineering framework to capture and organize the vital engineering knowledge and processes within a unified object-oriented part model.

- AML's underlying virtual layer architecture enables the seamless integration of engineering tools to automate the entire engineering cycle from conceptual design to production.

- WDE creates a distributed network of designers working on the same analysis model concurrently

ASTROS


OUR FUTURE
OUTPUT
THROUGH H PC
STRUCTURES & DYNAMICS
AIRLOADS
CONTROL RESPONSE
EXECUTIVE DATA BASE
OPTIMIZATION
AEROELASTICITY
SENSITIVITY ANALYSIS
MDO
MSRC
ASTROS
INPUT
OUR HERITAGE

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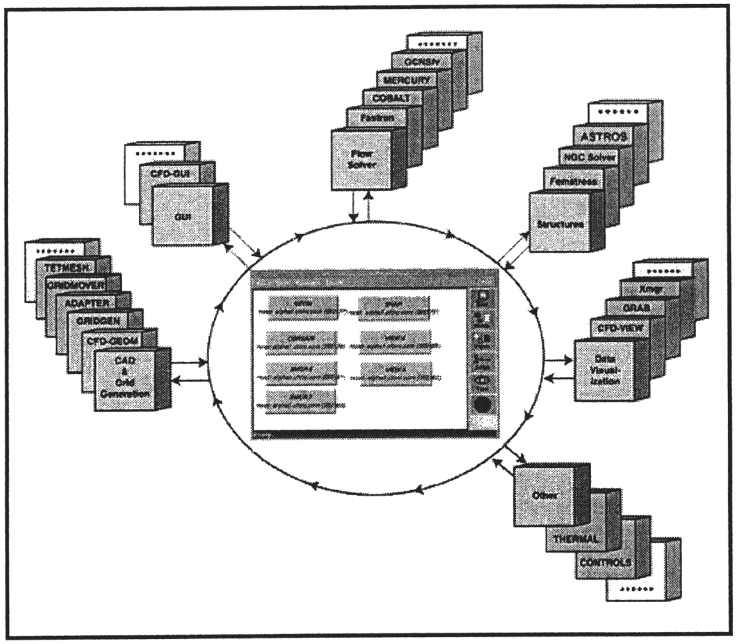
MDICE CONCEPTUAL OVERVIEW

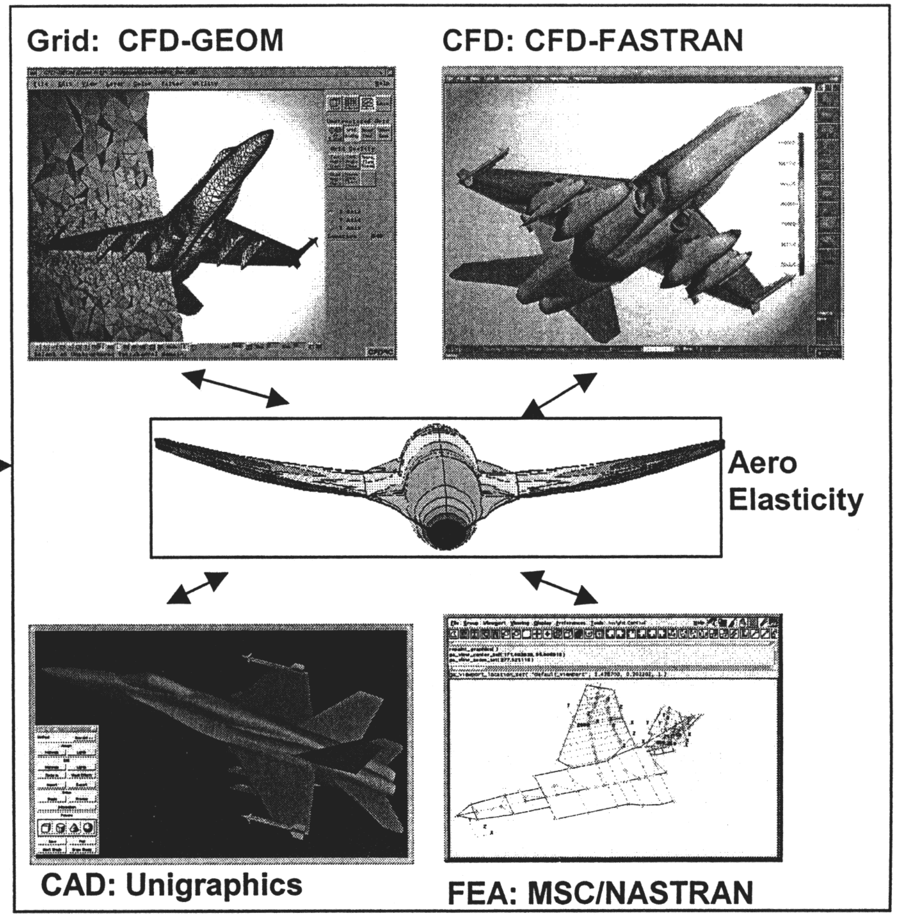
AIR VEHICLES DIRECTORATE

MDICE enables engineering programs of various disciplines and sources to function as ONE coupled multi-disciplinary application in a parallel distributed computing environment

13-108



MDICE
Multi-Disciplinary
Computing Environment

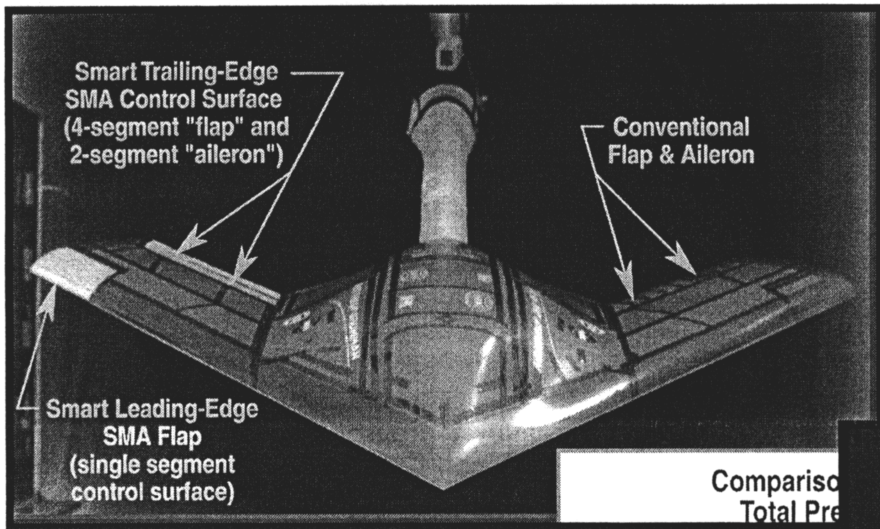


MDICE Application Example: Fluid-Structure Interaction

BRIAN SANDERS
AFRL/VASD

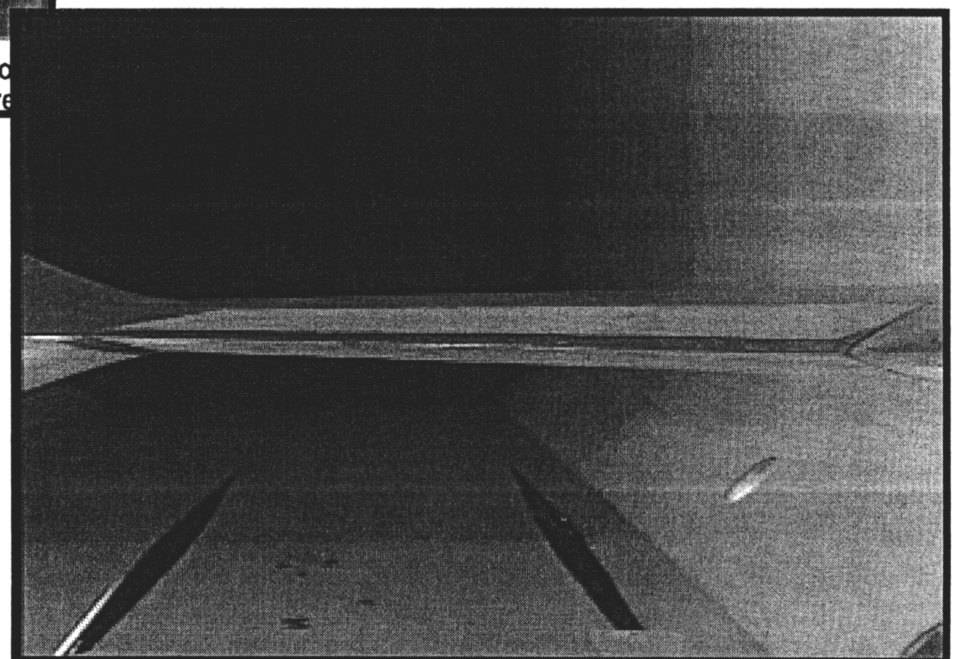
ADAPTIVE STRUCTURES

Conformal Control Surfaces
Smart Wing Program



Northrop Grumman

Conformal control surfaces may relieve some thermal management issues

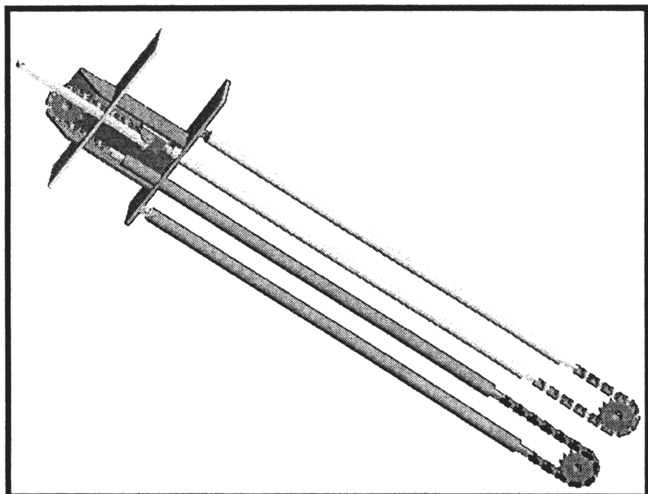


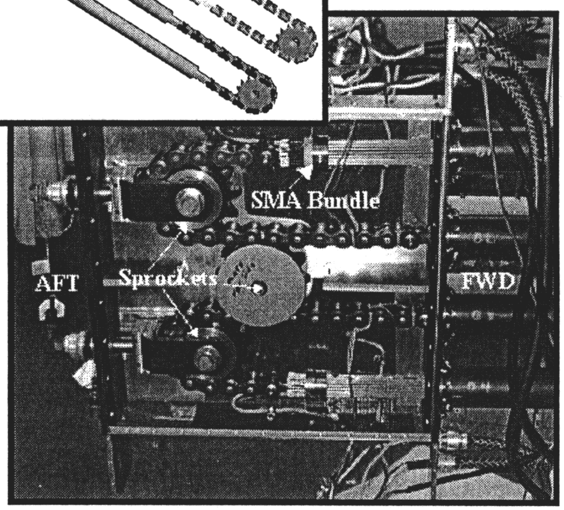
B-110

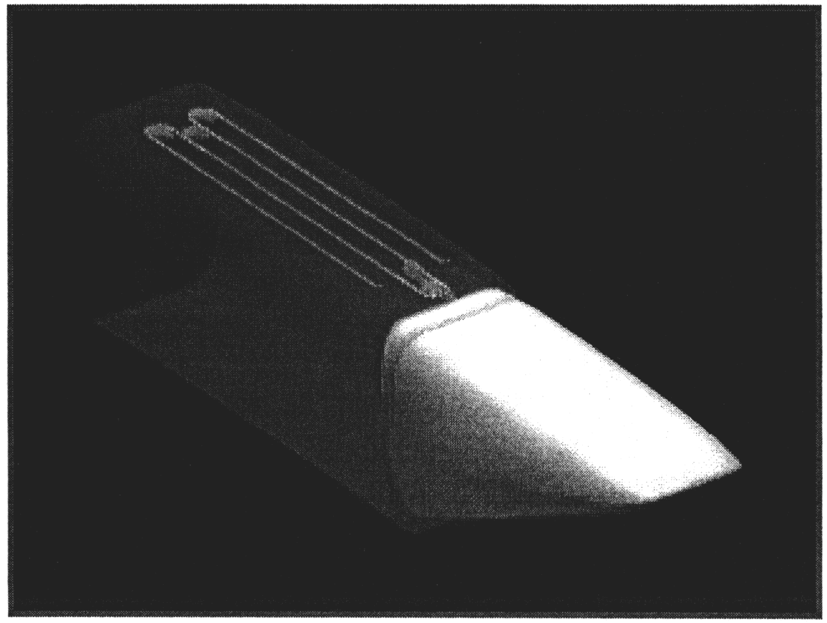
Variable Geometry Inlets
DARPA SAMPSON Program

B-111

Boeing

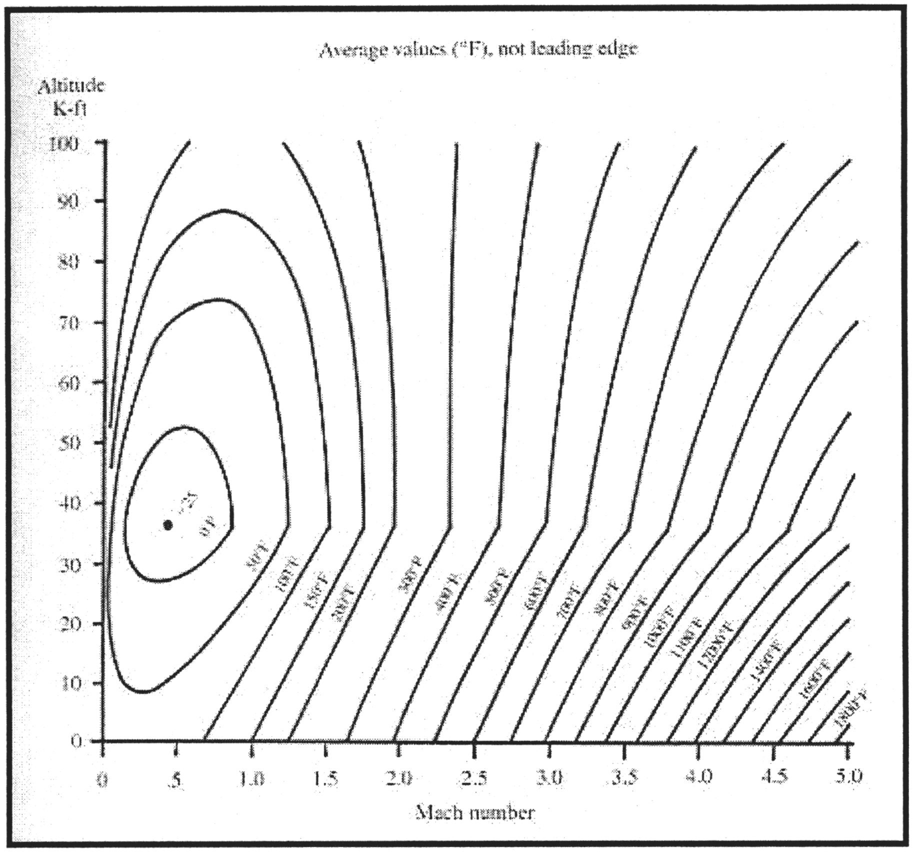




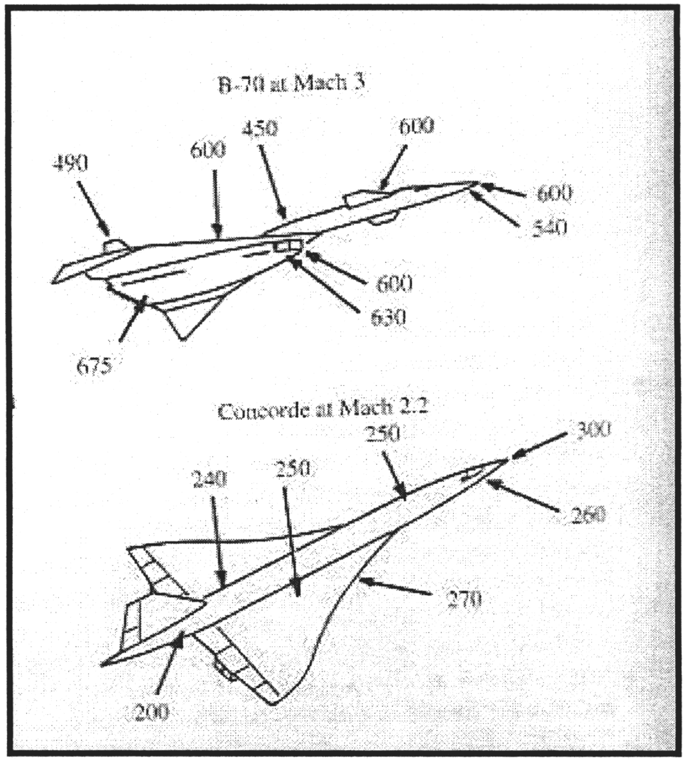


Variable geometry inlets are most useful at supersonic speeds

Energy Harvesting



Approximate Skin Temperatures



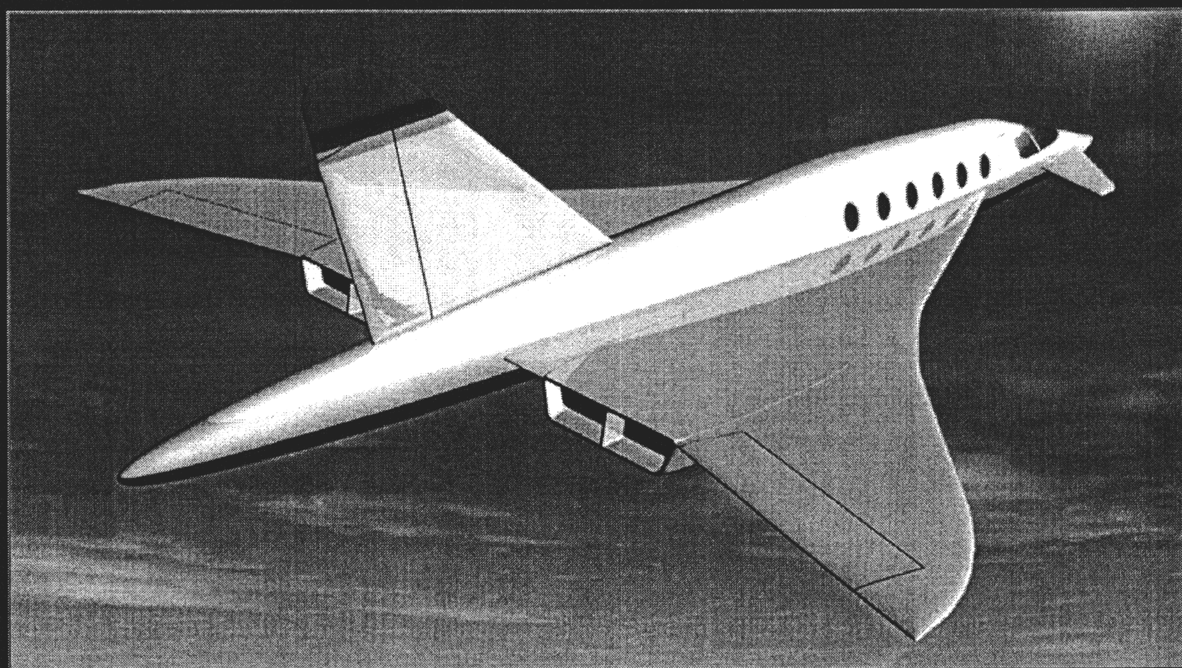
Supersonic Skin Temperatures

Can existing thermal energy be used to drive actuation systems (e.g. SMAs)

B-113

Structures and Materials Technologies for High Speed Flight Vehicles

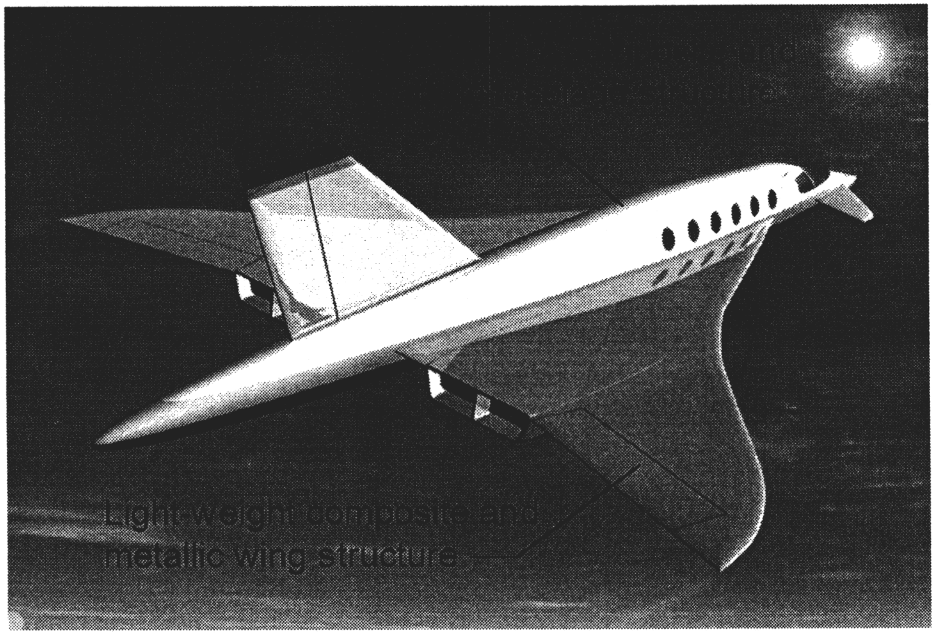
Dennis L. Dicus & Michael P. Nemeth
Structures & Materials
NASA Langley Research Center



DARPA QSP Focus Group Meeting on
Structures & Materials and Structures
June 26, 2001

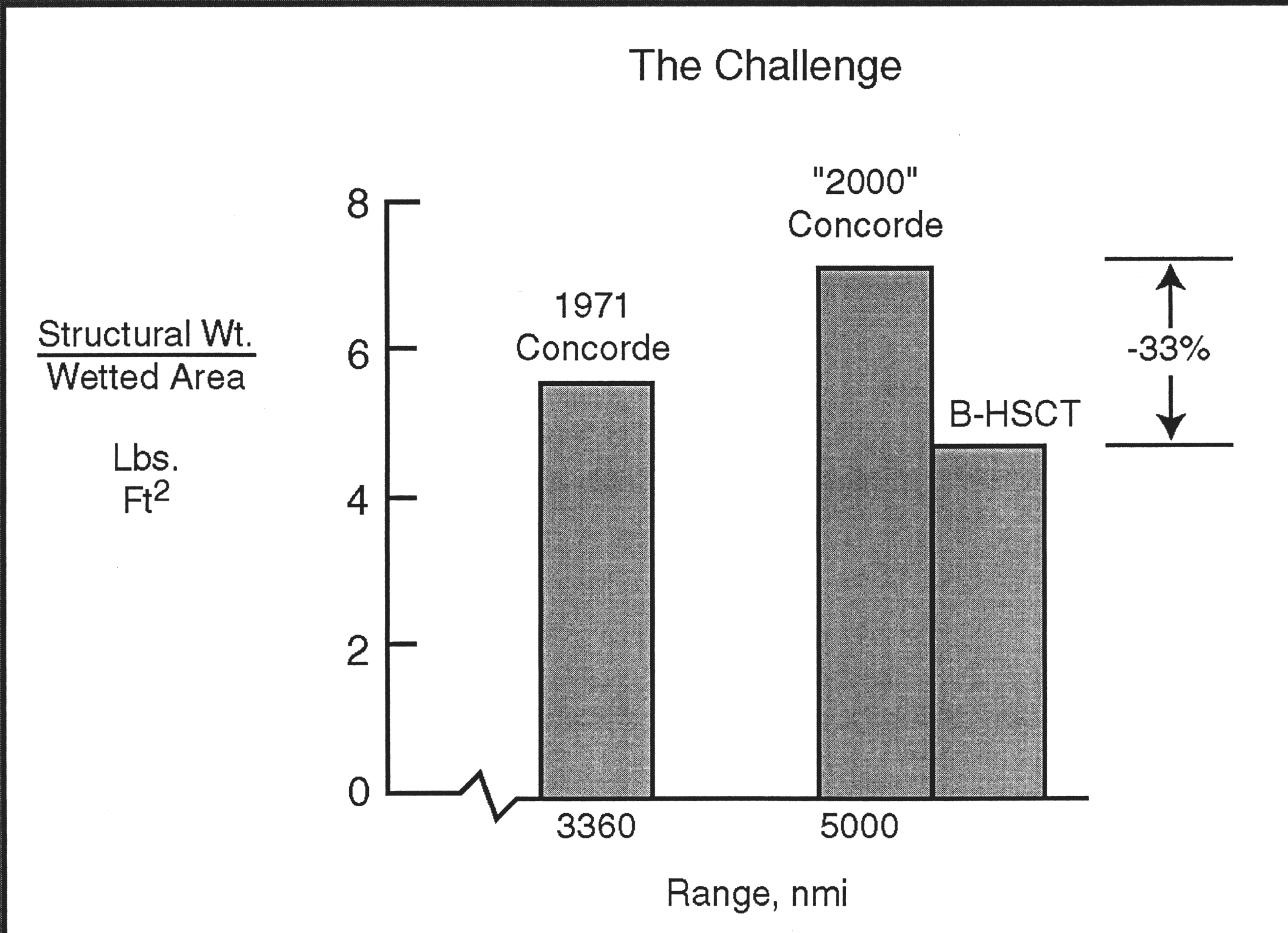
13-114

Structures and Materials Technologies for High-Speed Flight Vehicles



- Advanced composite materials and processing
- Advanced elevated-temperature aluminum alloys and processing
- Lightweight wing and fuselage structures
- Advanced structural analysis and design technologies

Weight Reduction Required for HSCT



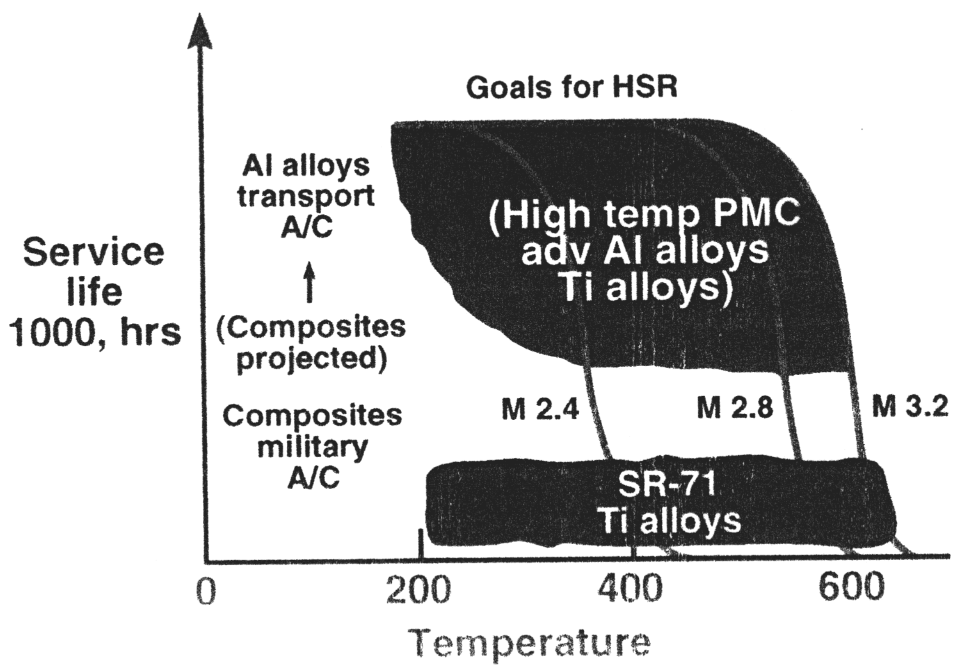
B-115

HSR AIRFRAME MATERIALS TECHNOLOGY

Key Issue

No long-term, high-temperature materials data base for HSCT airframes (60,000-hr design life, 120,000-hr fatigue life)

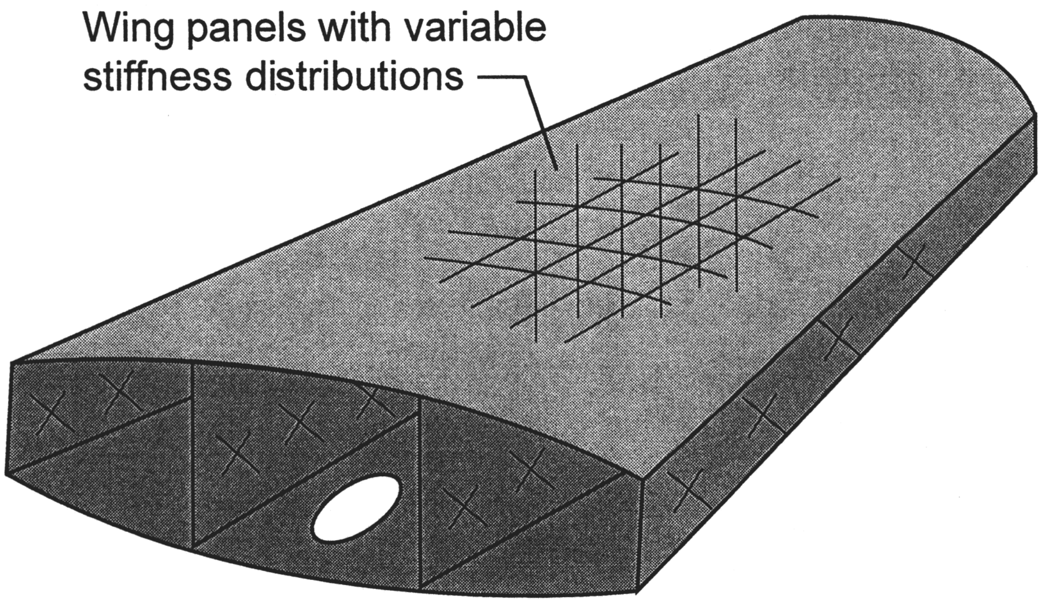
B-116



Key technology needs

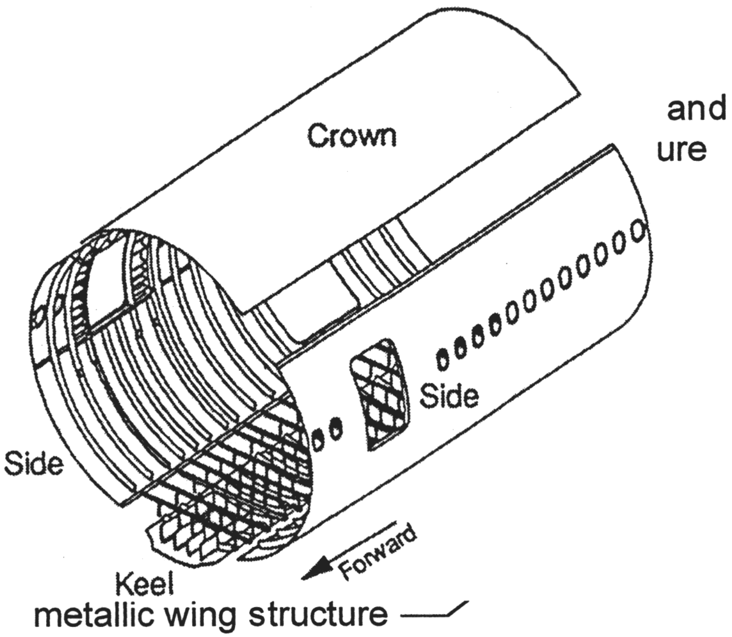
- Life prediction methodology
  - Accelerated test procedures
  - Long-term flight simulation durability
- Demonstrated 300°- 500°F polymer matrices, adhesives and sealants for ≥60,000-hr lifetimes
- Demonstrated 300°- 600°F lightweight metals and metal matrix composites for ≥60,000-hr lifetimes

Light-Weight Wing Structures With Variable Stiffness Distribution



- Potential of significant weight reduction
- Stiffness tailoring to suppress flutter response with no weight increase
- Tailored wing can enable advanced aerodynamic performance

Light-Weight Fuselage Structures with Variable Stiffness Distribution

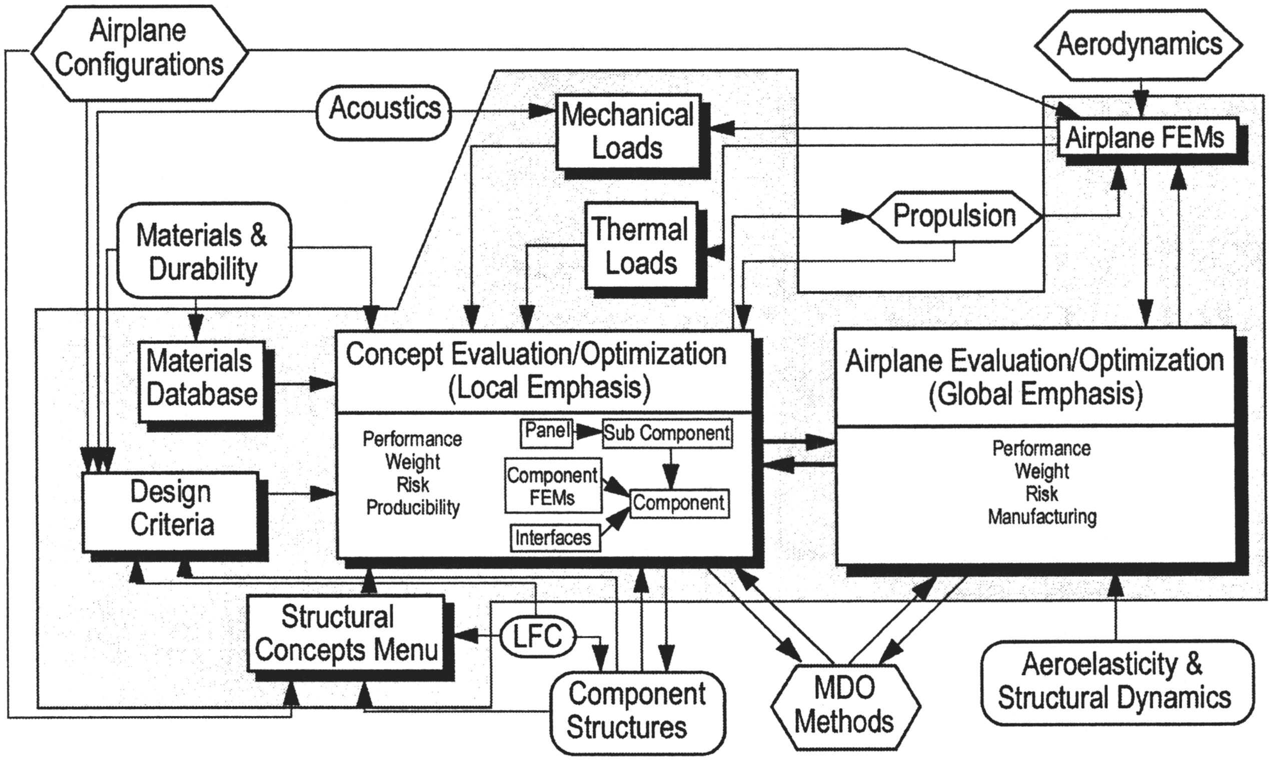


13-118

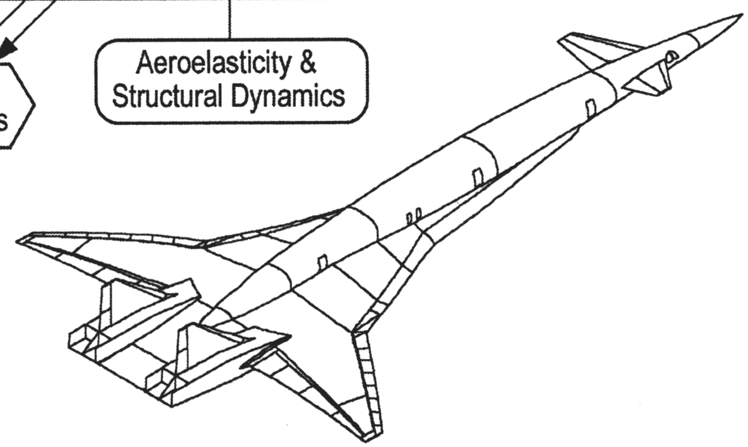
- Potential of significant weight reduction and assembly cost reduction
- Crown, side, and keel panels with different concepts and stiffness distributions
- Stiffness tailoring to suppress undesirable dynamic responses and to control internal load distribution
- Improved structural integrity for higher-altitude cruise conditions

Recently Developed **Integrated Design Processes** Enable Viable Supersonic Configurations

B-119



SST Designed with Integrated Process Having No Weight Penalty for Preventing Wing Flutter

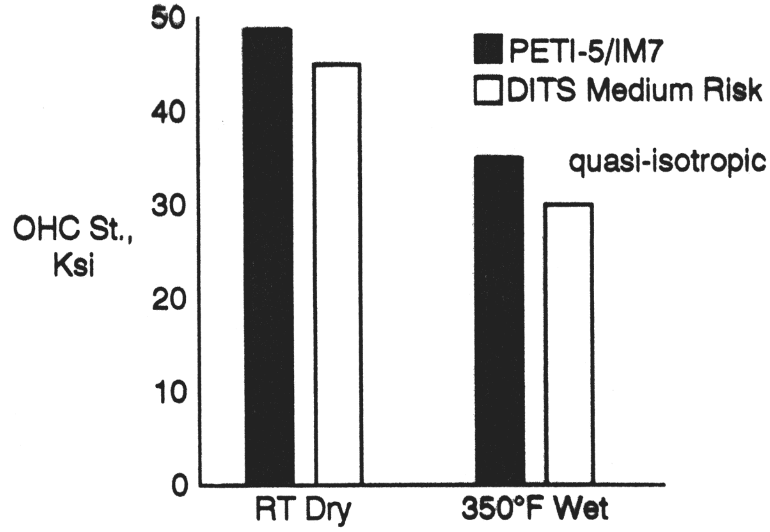


PETI-5 Composites for HSCT

Significance

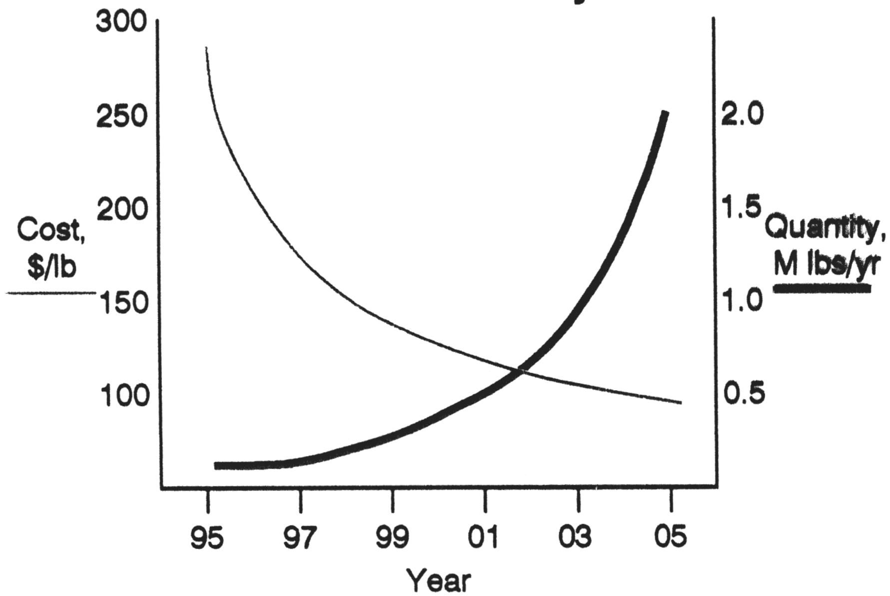
- Resolved enabling HSCT Technology problem on composites
- PETI-5 composites selected for HSCT Durability and Structures Activities
- Provided material to meet other aerospace applications

Composite Performance



B-120

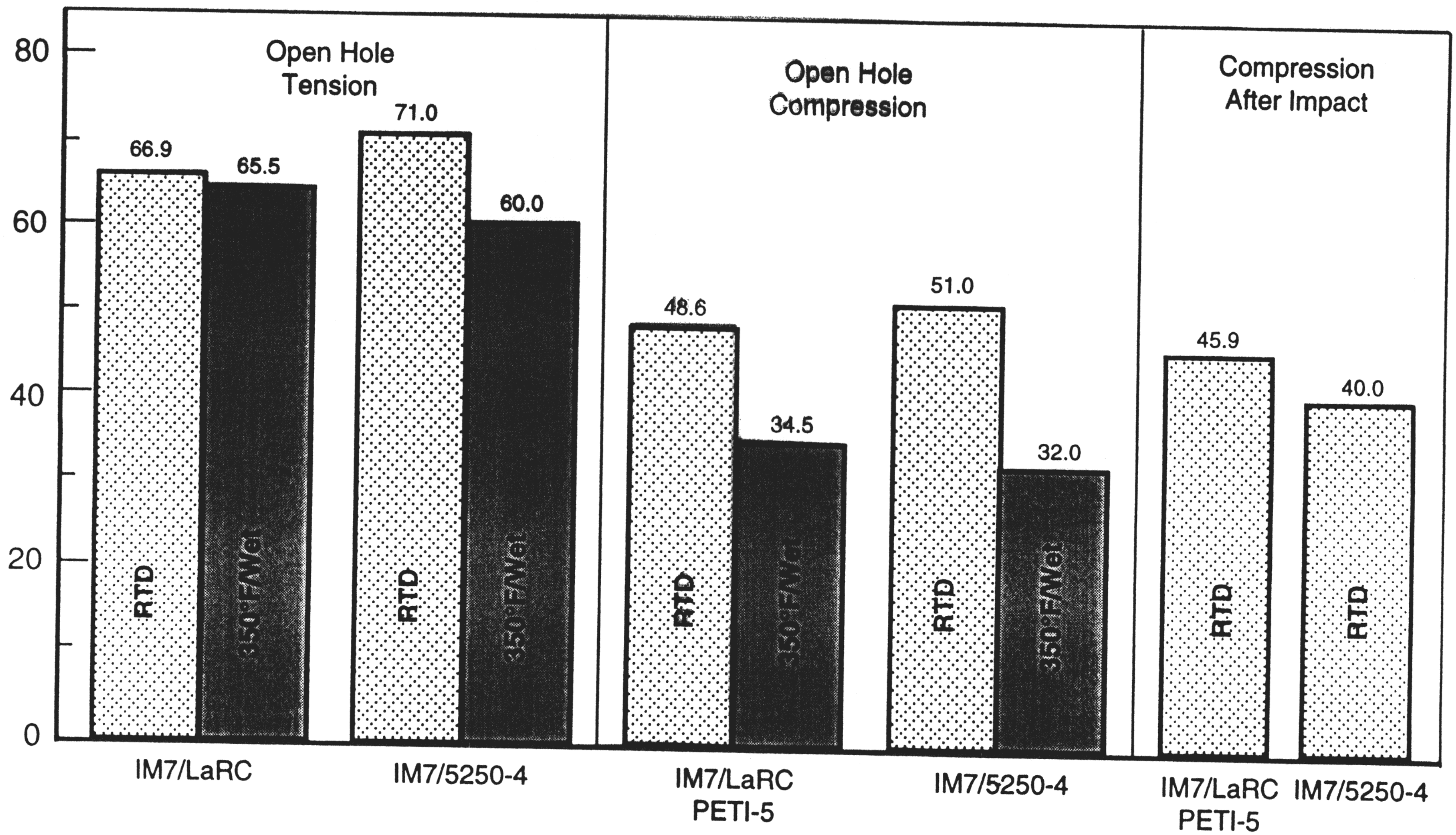
Cost and Market Projections



PETI-5 Composite Status

- Readily processable
- Excellent overall composite properties
- Available in large quantities
- Safe for workers
- Industry acceptance

Mechanical Properties



Properties Superior to BMI

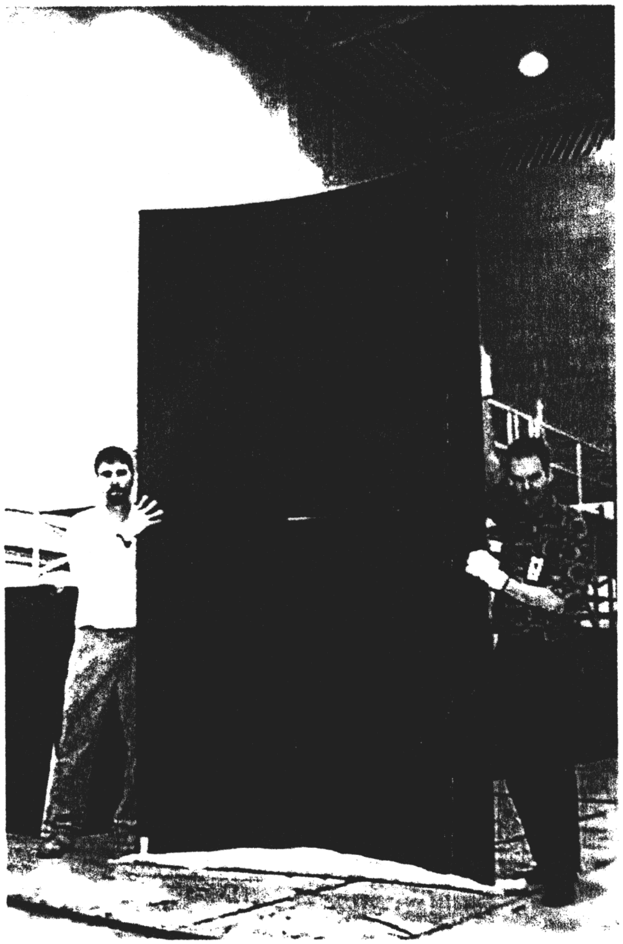
NORTHROP GRUMMAN

V97-RD/064.ppt

B-121

PETI-5 Wet Sandwich Processing

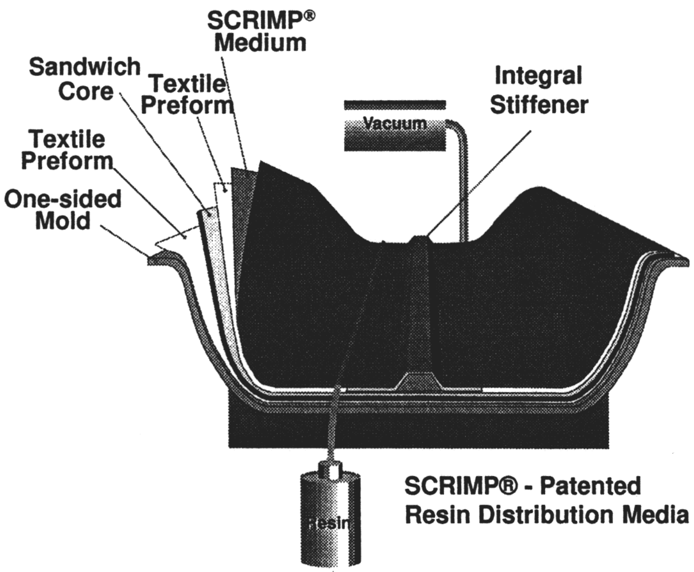
B-122



- 28 ply, 6 ft x 10 ft, IM7/PETI-5 facesheets pre-dried using 232°C (450°F)/4 hours
- 20 piece high and low density titanium core blanket pre-bonded using FMX5-3 (PETI-5)
- Facesheets bonded to core blanket using two layers of FMX5 (PETI-5)

The Boeing Company, Seattle
HSCT Group

Advanced Composite Materials and Low-Cost Vacuum Assisted Resin Transfer Molding (VARTM) Process



SCRIMP® - Patented Resin Distribution Media

Advantages of low-cost RTM process:

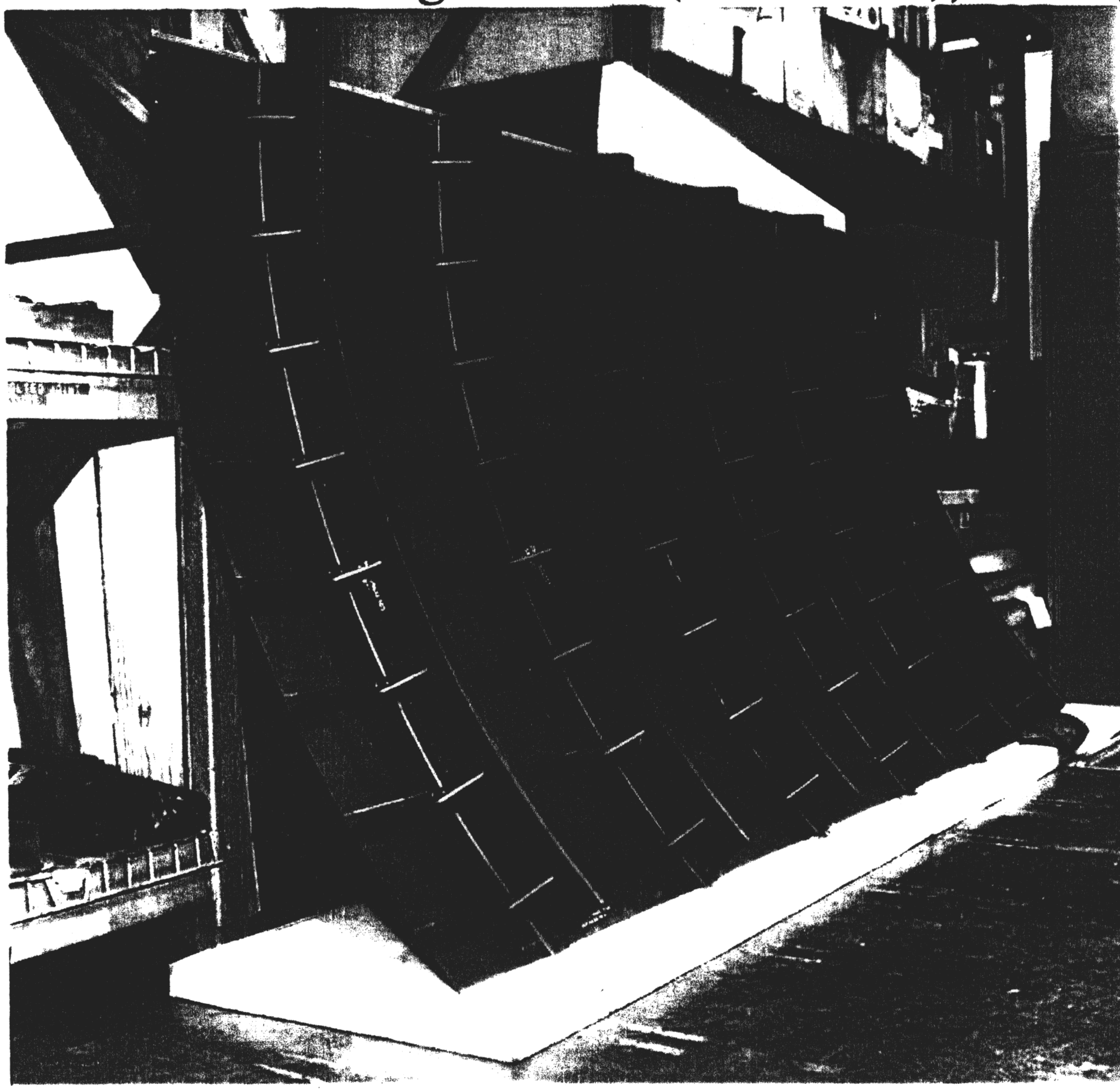
- Resin and fiber used in lowest cost form
- Prepreg process eliminated
- Freezer storage & shelf life problems eliminated
- Low-cost, one-sided tooling
- Low energy, low pressure out-of-autoclave processing
- Utilizes net-shape, damage tolerant textile preforms
- Large integral structure minimizes secondary bonding and fastening

Challenges for aircraft applications:

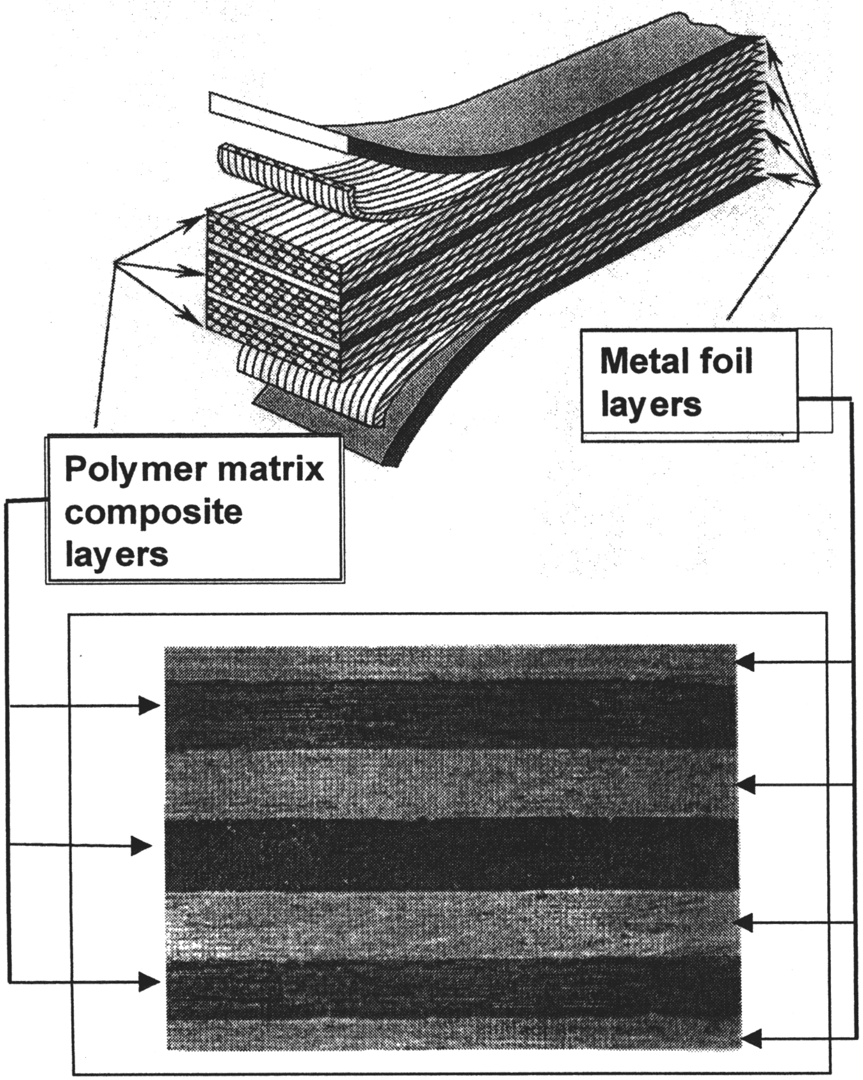
- *Out-of-autoclave cure resins with adequate properties*
- *Dimensional tolerances with low-cost tooling*

B-123

PETI-5/IM7 Skin Stringer Panel (6 ft x 10 ft), Boeing St. Louis



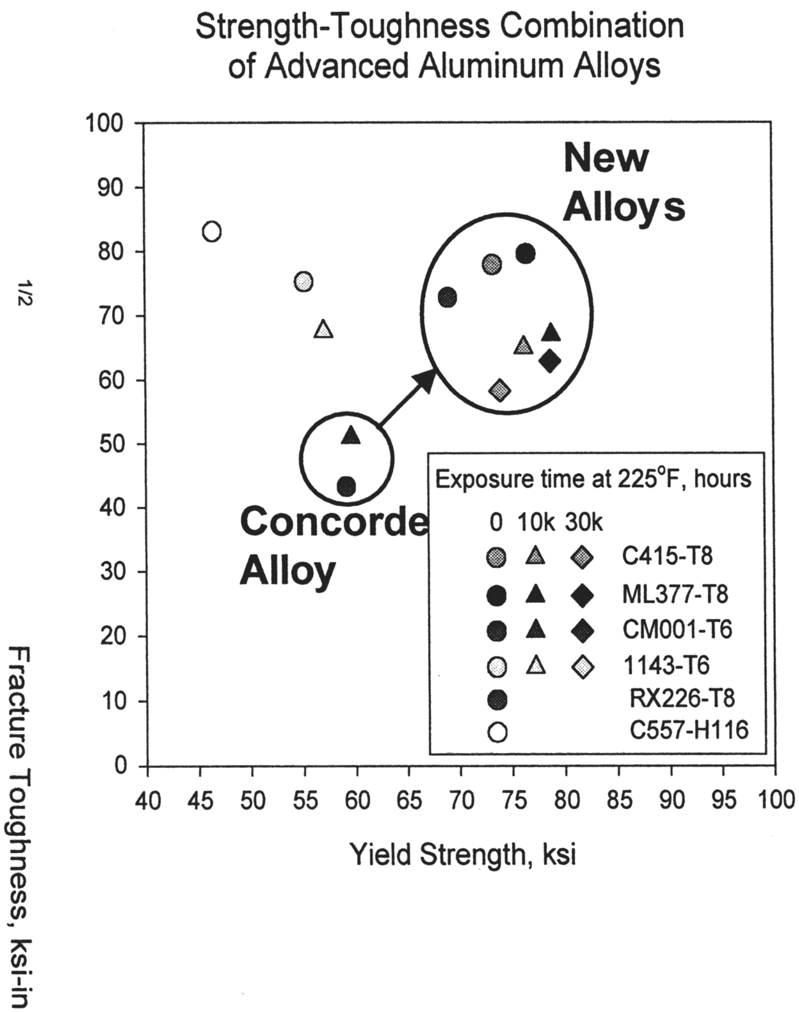
Metal/Polymer Matrix Composite Hybrid Materials for Wing and Fuselage Structures



B-125

- Improved strength & stiffness to density ratio → Lower weight
- Improved fatigue life & crack growth resistance → Longer life
- Metal-like lightning strike protection → improved safety
- Enhanced damage tolerance → reduced repair
- Metal outer layers → environ-mental protection, durability
- Unequal modulus → improved in-plane damping

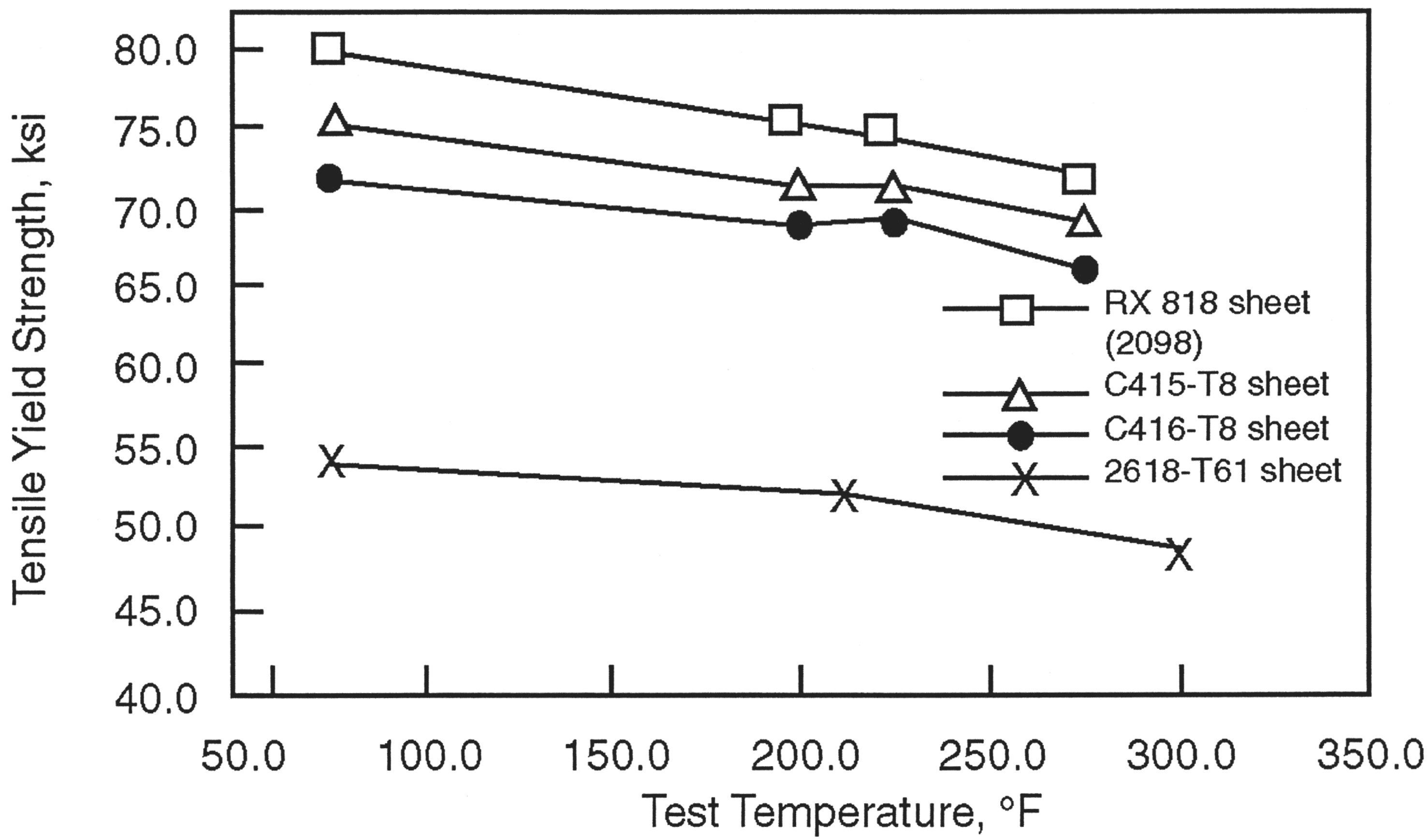
Elevated Temperature Aluminum Alloys Demonstrate Property Improvements over Existing SST Alloys



- **Significant Strength-Toughness improvements over Concorde alloy**
- **Properties retained after 30,000 hours exposure at 225°F (Mach 2 conditions)**
- **Superior creep resistance compared with Concorde alloy**
- **Newer developmental alloys show promise for improved properties**
  - **higher strength and toughness with improved thermal stability**
  - **superior corrosion resistance**
- **Newer ultra-low-density alloys offer significant weight reduction with improved properties**

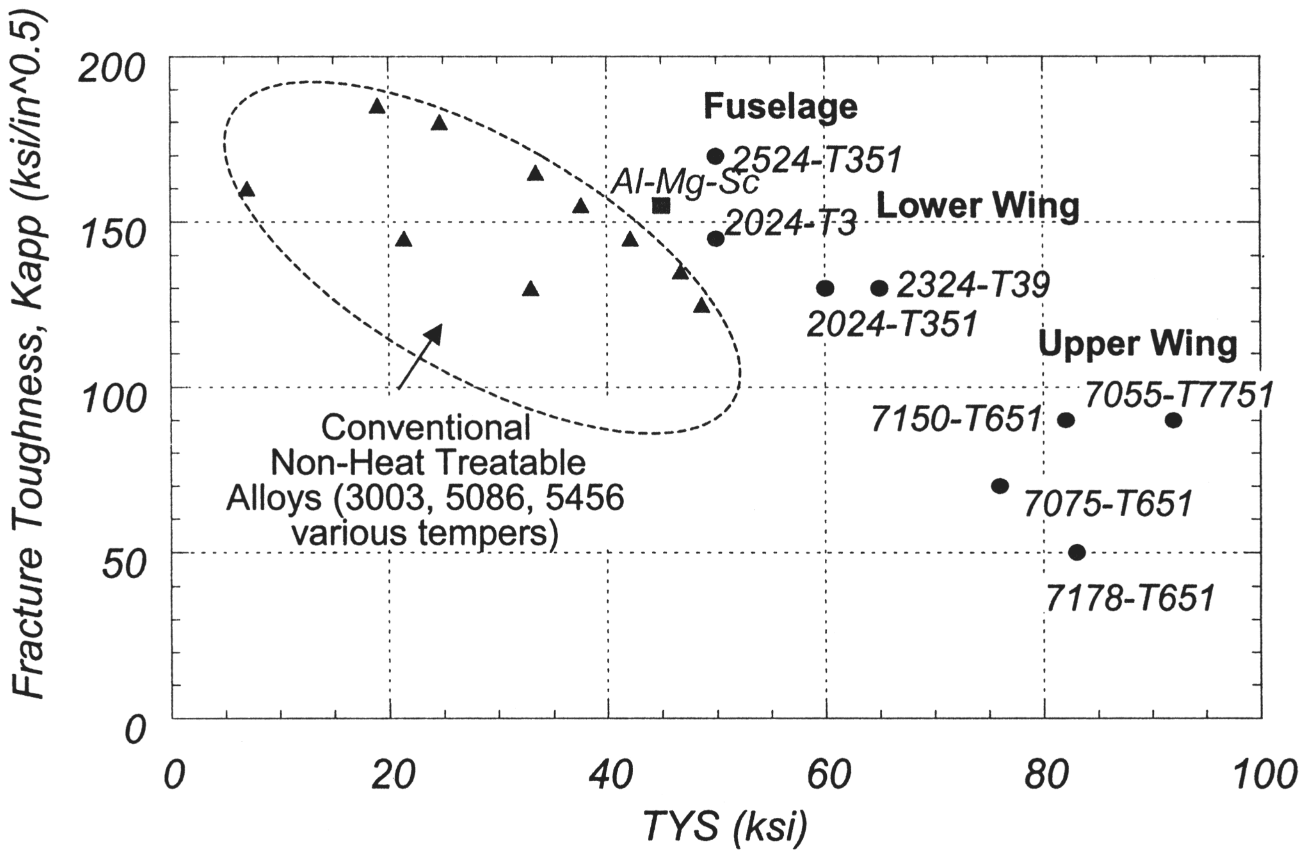
B-126

Elevated Temperature Yield Strength of New HSR Aluminum Alloys



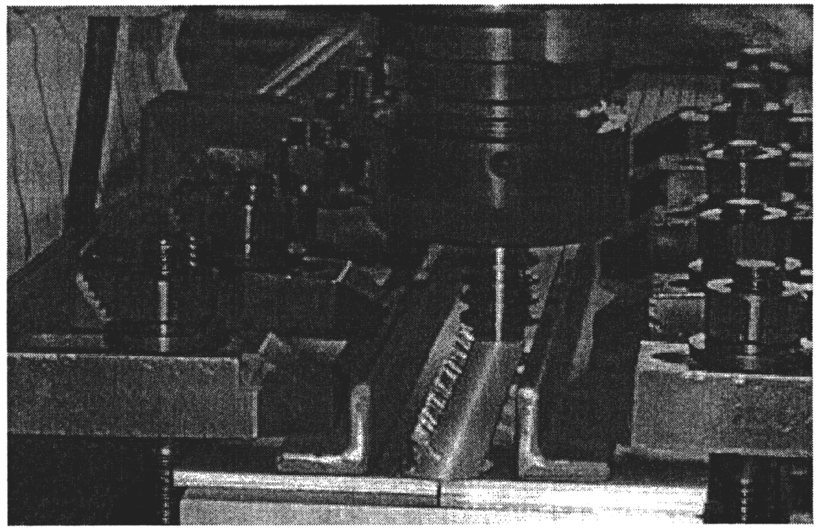
B-127

Strength-Toughness Performance of Al-Mg-Sc Compared with Airframe Skin Alloys



Benefits of Al-Mg-Sc:	
High strength-toughness combination	Non-heat treatable alloy
Good corrosion resistance	Density = 0.096 lb/in^3

Benefits of **Friction Stir Welded Joints** vs Riveted Joints



Generates Weight Savings
- contributes to sonic boom, fuel-use and emission reductions
- eliminates fastener and butt strap weight
- eliminates fuel sealants

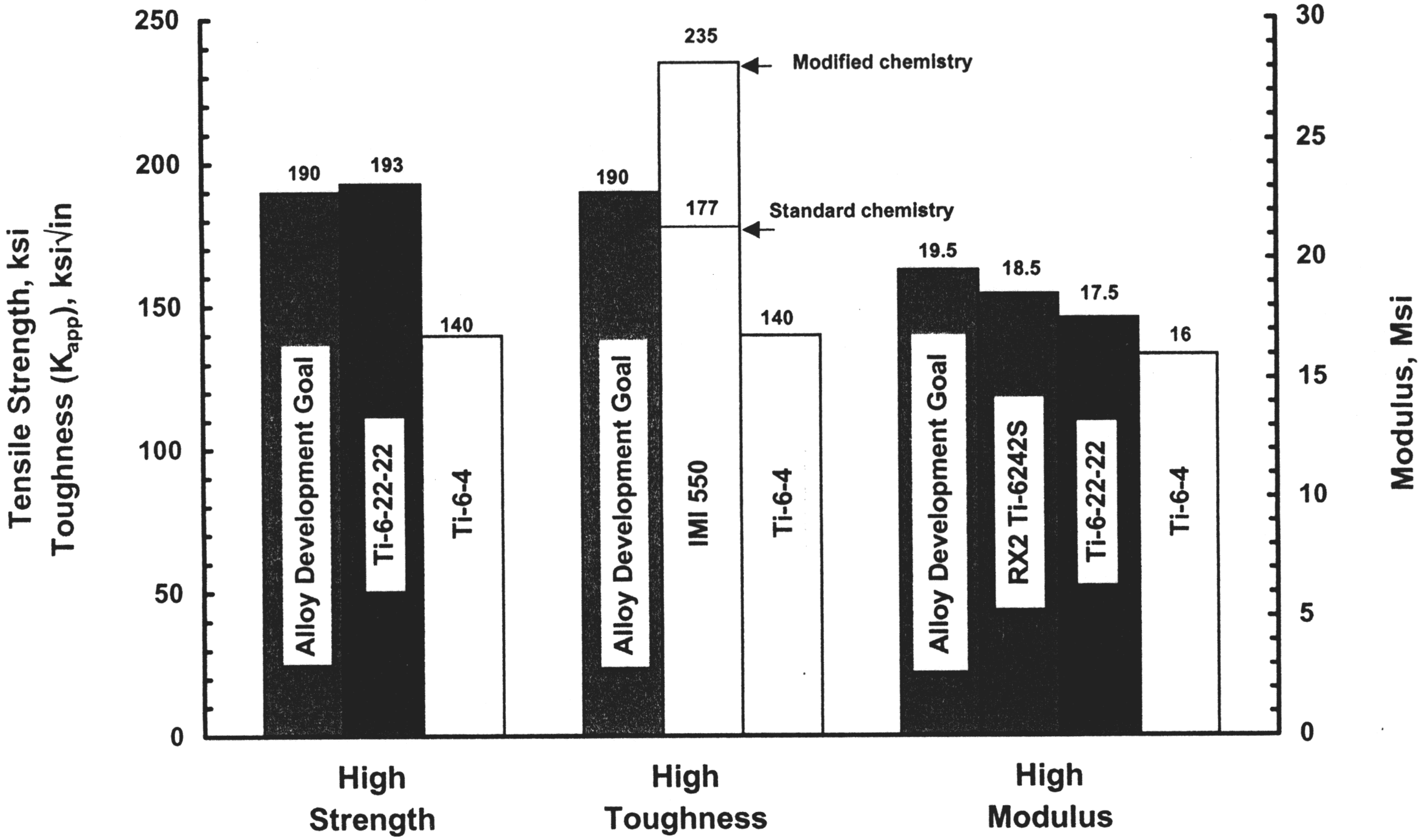
Generates Cost Savings:
- reduces part count
- reduces assembly costs
- reduces design costs
- reduces maintenance costs

Improves Joint Quality and Reliability
- eliminates of stress concentration at fastener holes
- improves fatigue performance though elimination of stress concentration
- eliminates interfaces, moisture ingress, fretting

Improves In-Service Performance
- improves fatigue performance to give increased inspection threshold intervals

Enables Innovative Designs
- process enables a fresh, “out-of-the-box” approach to structural concept design
- enables decoupling of geometry changes from load transfer/joining function

Heat Treat Selection for Primary Titanium Sheet Down-Select Alloys



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High Strength Variant

ST: 1650°F ± 25°F/ 30 min
Cool: 100° to 400°F/min
(Between ST & ST-180°F)
Age: 930°F ± 25°F / 8 hrs

High Toughness Variant

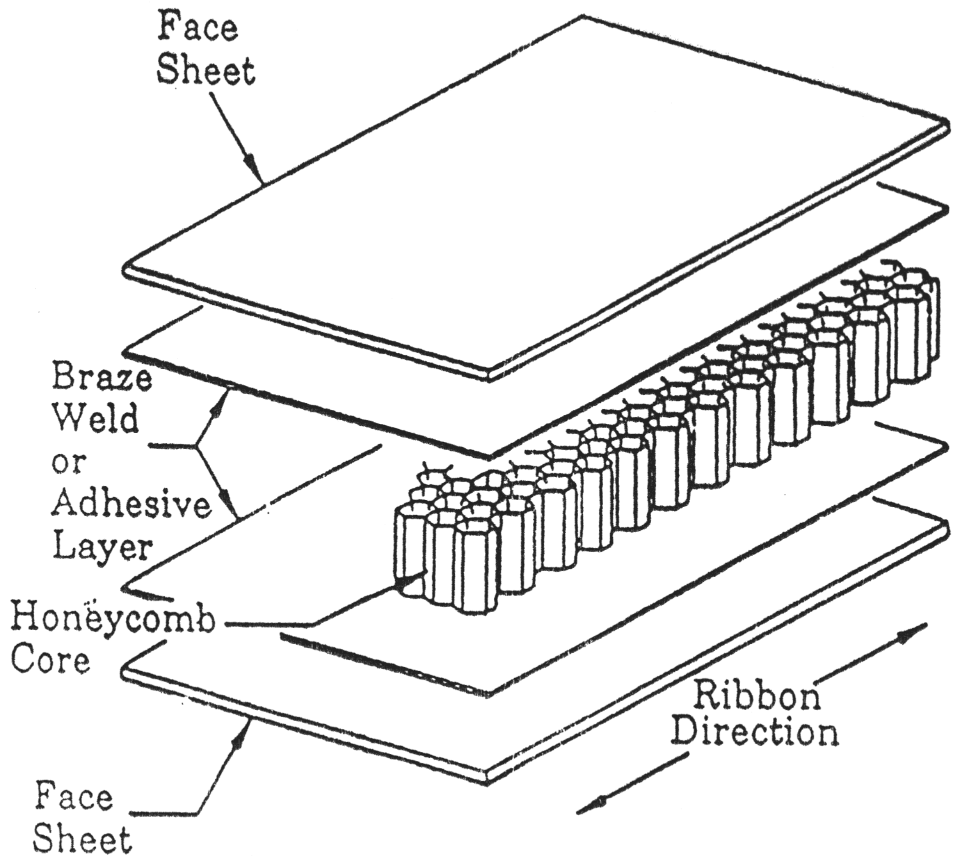
ST: $ß_T$ - 50°F ± 15°F/ 30 min
Cool: Furnace cool @ ~ 5° to 50°F/min
Age: 930°F ± 25°F / 8 hrs minimum

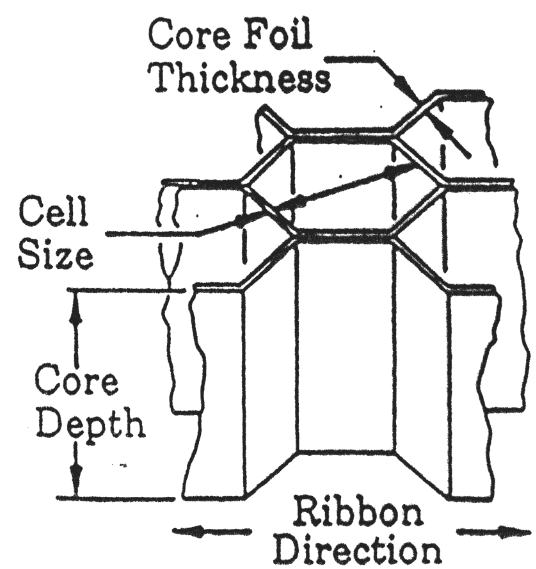
High Modulus Variant

ST: $ß_T$ - 10°F to $ß_T$ - 40°/ 2 hrs
Cool: Controlled cooling
(60°F/min ± 30°F / min
Age: 1100°F / 8 hrs

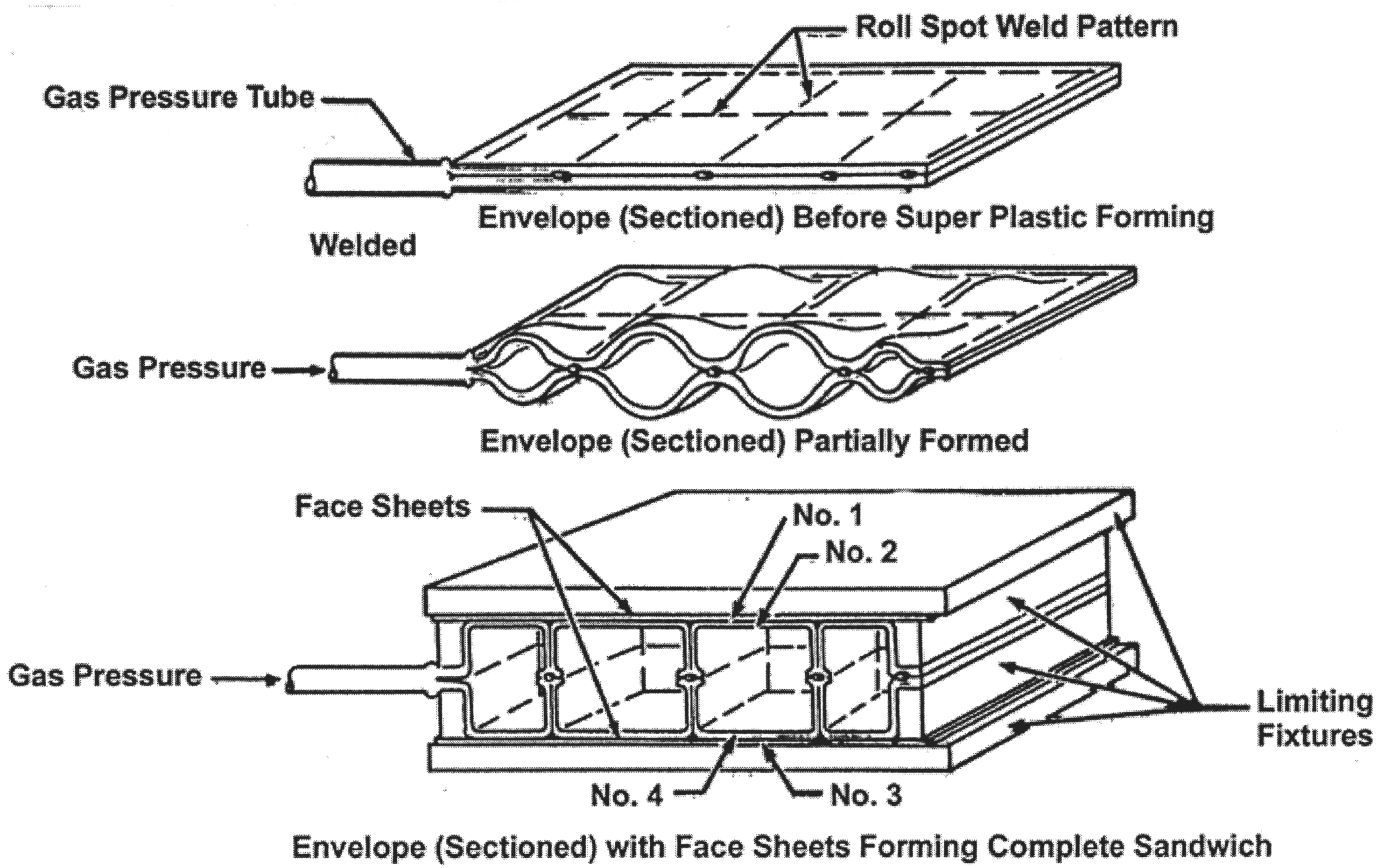
Assembly of Titanium Honeycomb Sandwich Panel and Core Configuration

High Speed Civil Transport



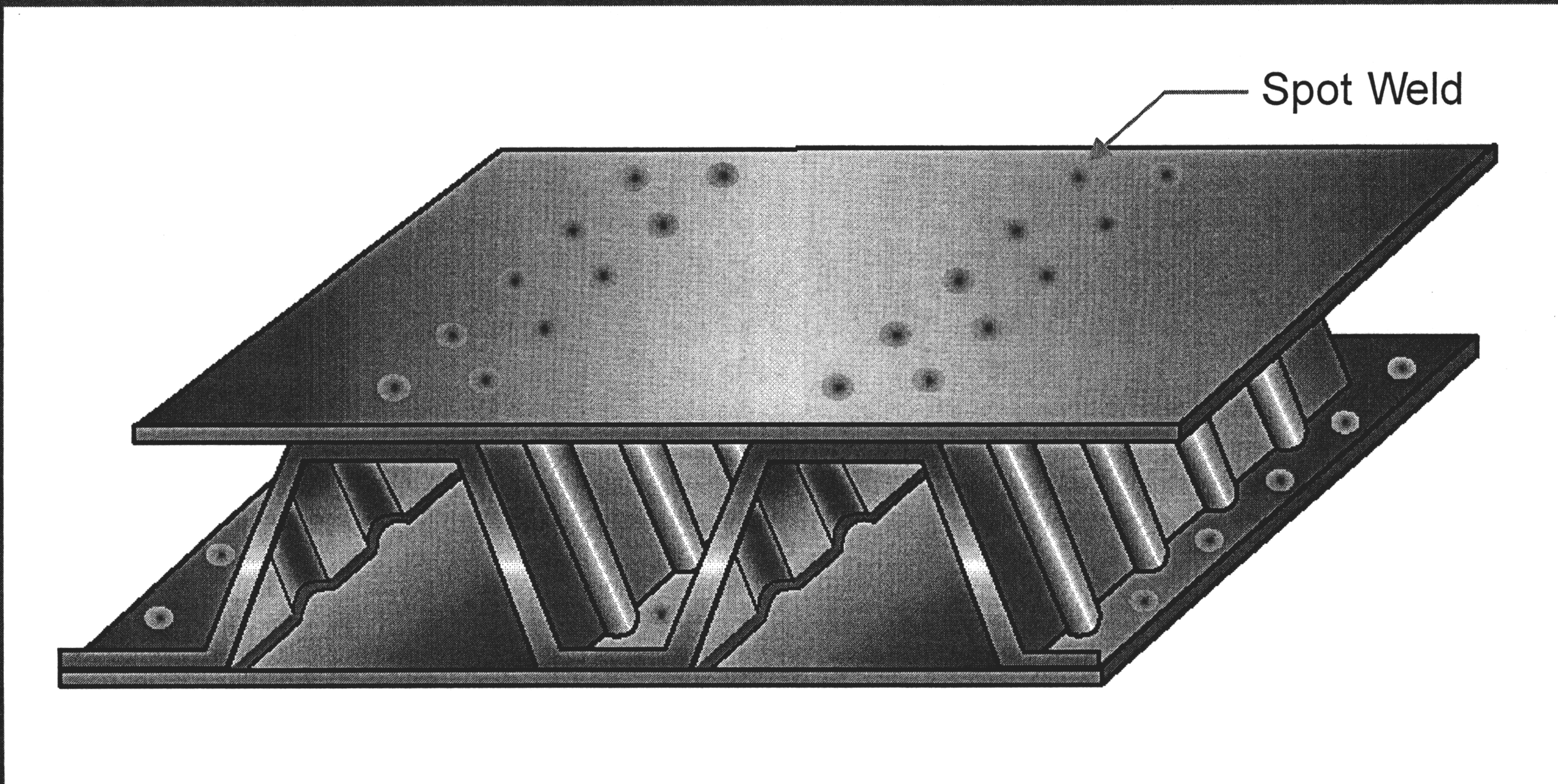


SPF/DB Titanium 4 Sheet Sandwich Fab



B-132

Weld-Bonded SPF Beaded Web Truss Core Sandwich



13-133

DARPA QSP FOCUS GROUP MEETING

ON

MATERIALS AND STRUCTURES

B-134

Haydn N.G. Wadley

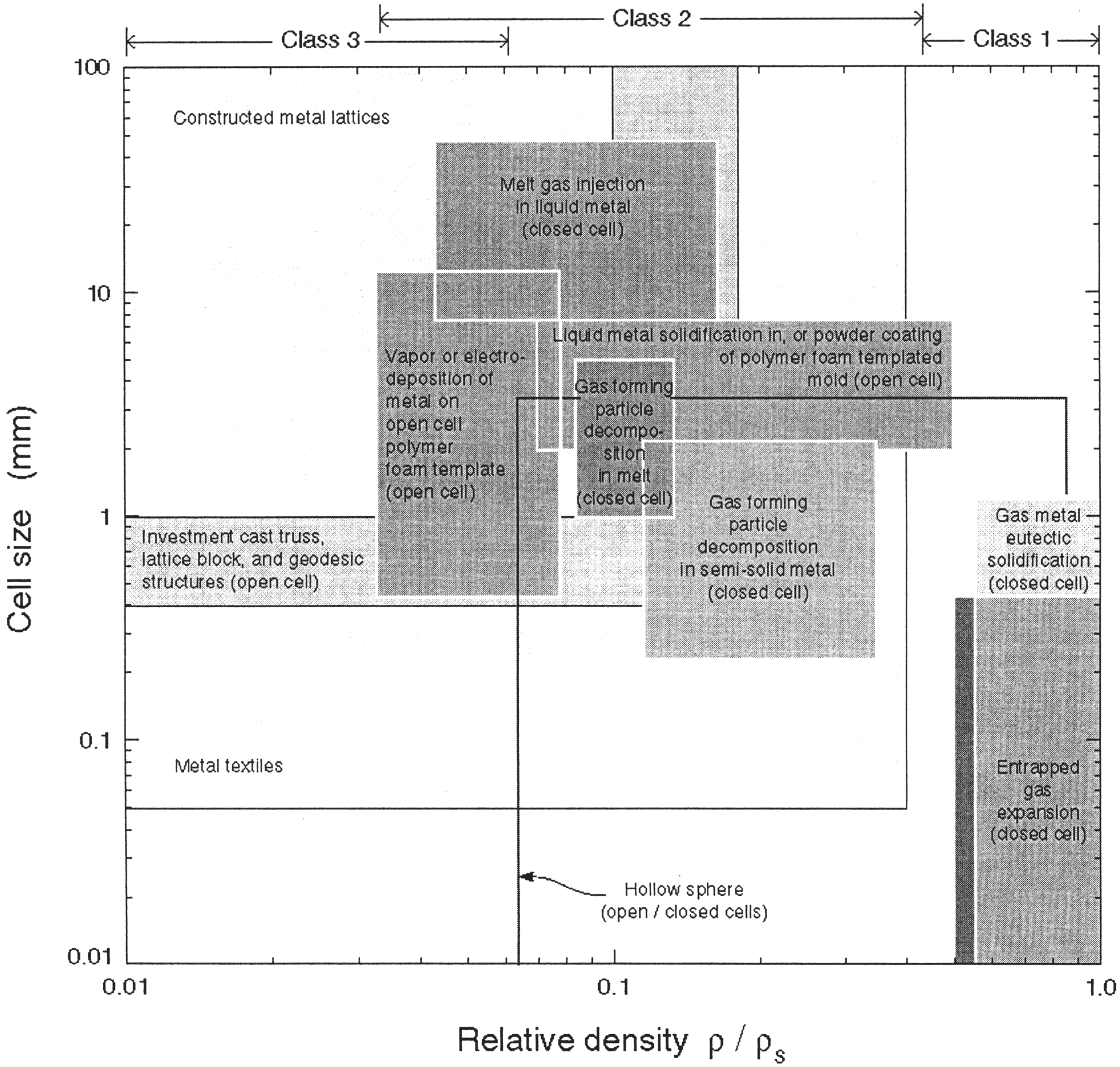
University of Virginia, Charlottesville, VA 22904

(434 924-0816/ haydn@virginia.edu)

Tuesday, June 26, 2001

Work supported by DARPA (Leo Christodoulou) and ONR (Steve Fishman)

Classes of 3-D Cellular Metals



B-135

Class 1

Porous metals: closed cell

$0.5 < \rho / \rho_s < 1.0$

Class 2

Stocastic metal foams: open / closed cell

$0.03 < \rho / \rho_s < 0.5$

Class 3

Periodic metal trusses: open cell

$0.01 < \rho / \rho_s < 0.02$

Cellular Metals

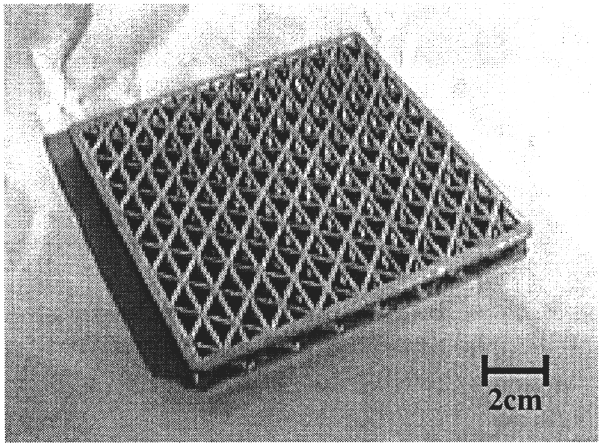
B-136

- **Cellular Metals**
  - Stochastic
    - Duocell
    - ALPORUS (FORMGRIP)
    - Cymat
    - Alulight
    - Porvair
    - Incofoam
    - DVD foam
    - Syntactic foam
    - Hollow sphere, etc.
  - Periodic
    - Prismatic
      - Rapid prototyped
      - Georgia Tech oxide precursor extrusion
      - Metal Extrusion
      - SPF/DB Honeycomb
    - Lattice / truss
      - Lattice block material (LBM)
      - Tetragonal truss
      - Woven microtruss
      - Constucted cellular solid
      - Geodesic structures
      - Electrodeposited microtruss

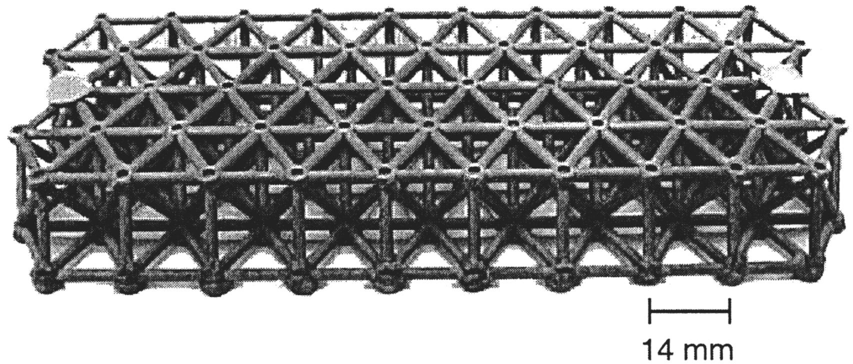
Topologies of Periodic Cellular Metals

B-137

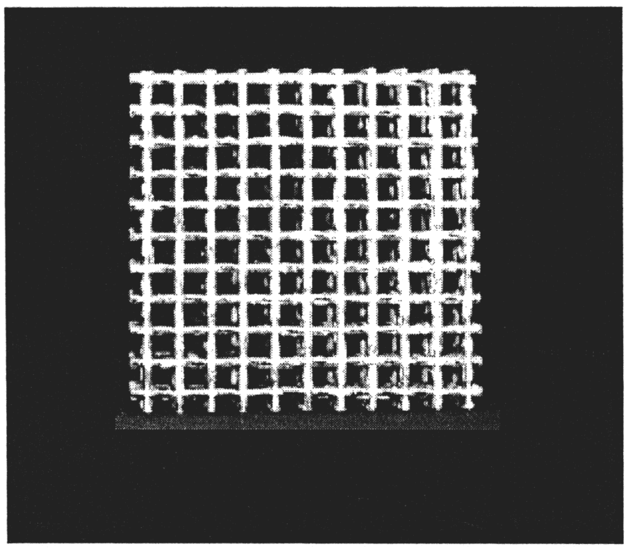
Lattice Block Material (Jam Corp)



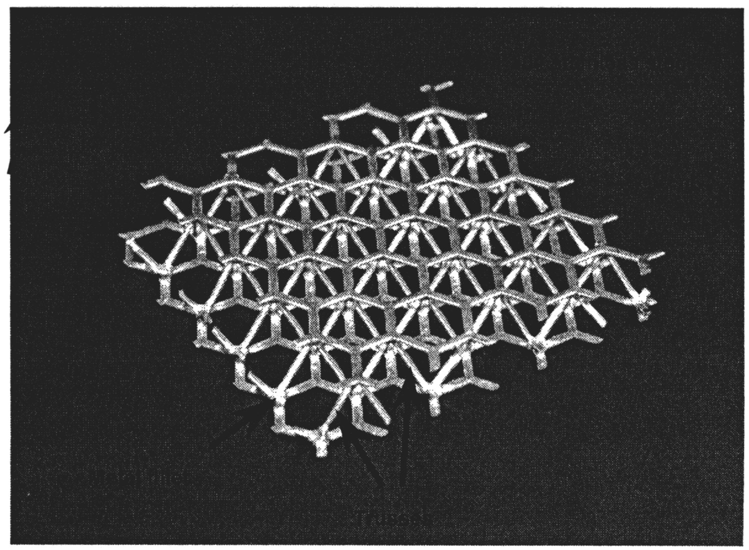
Tetragonal Truss Core Panels (MURI)



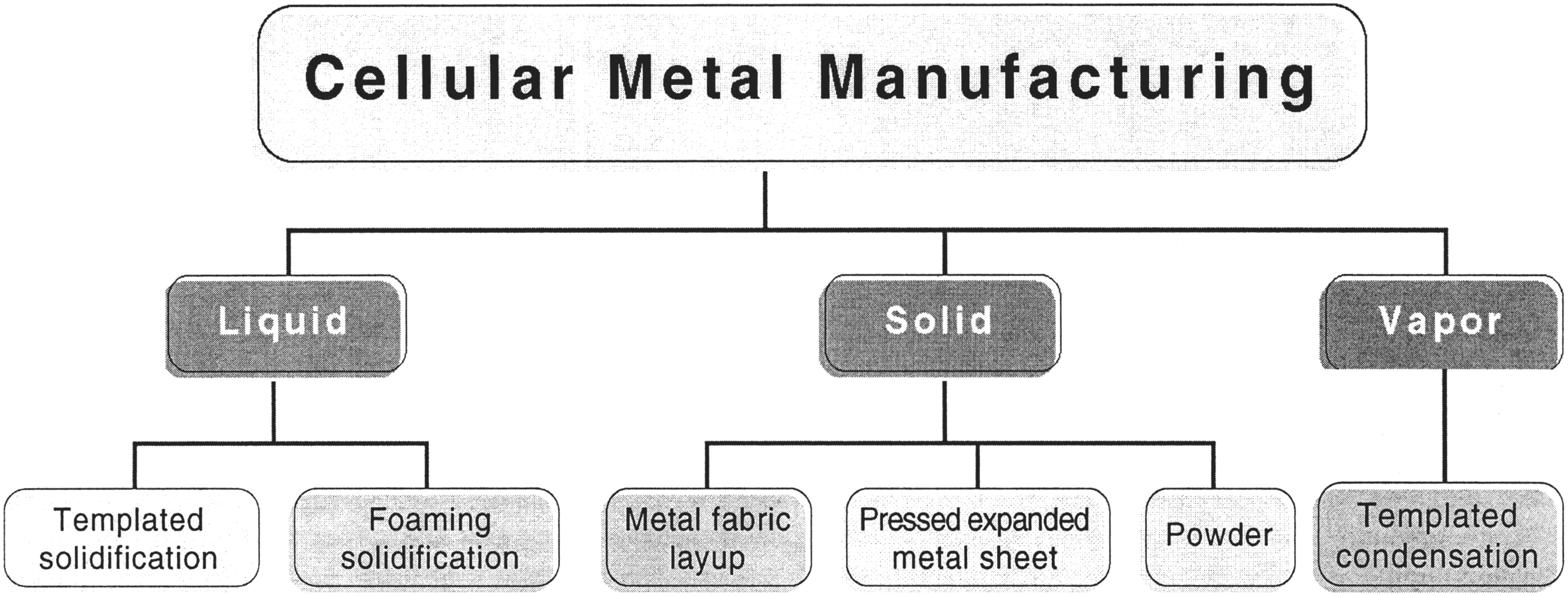
Woven Micro Truss (MURI)



Constructed Cellular Solid (MURI)



Cellular Metal Manufacturing



B-138

Periodic Cellular Metals

B-139

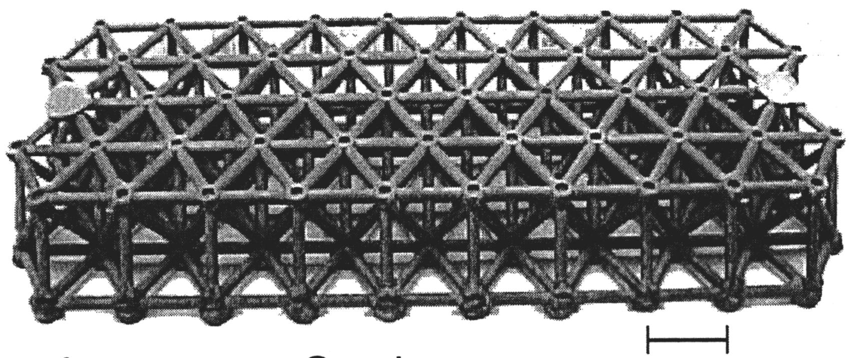
Tetragonal Lattice Structure

Harvard MURI: (Harvard/Princeton/Cambridge/MIT/UVA).

Process: polymer template/investment casting. Infiltrate with ceramic slurry, burnout polymer, fill with liquid metal, solidify.

Materials: Cu-2% Be, Bronze, Al, Ni, Fe casting alloys.

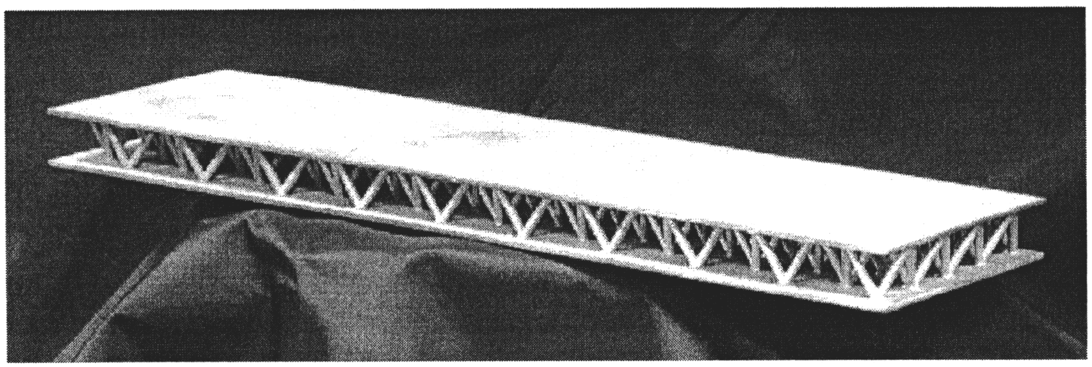
13-140



Injection Molded + Investment Casting Route

14 mm

Rapid Prototyping +Investment Casting



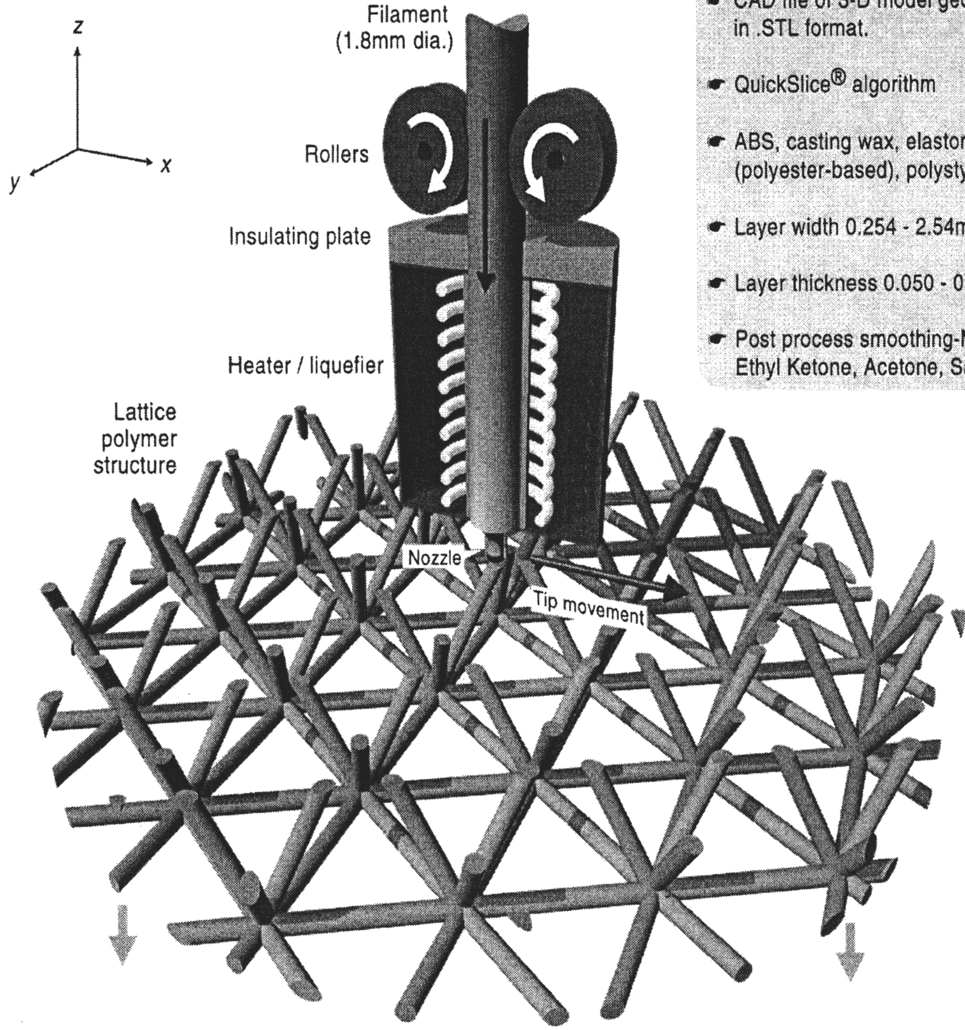
Cell Size: 2-20mm ρ/ρ_s: **1-10%**

Reference:

S. Chiras, D.R. Mumm, A.G. Evans, N. Wicks, J.W. Hutchinson, S. Fichter, K. Dharmasena, and H.N.G. Wadley, International Journal of Solids and Structures, submitted (2001).

Fused Deposition Modeling Process

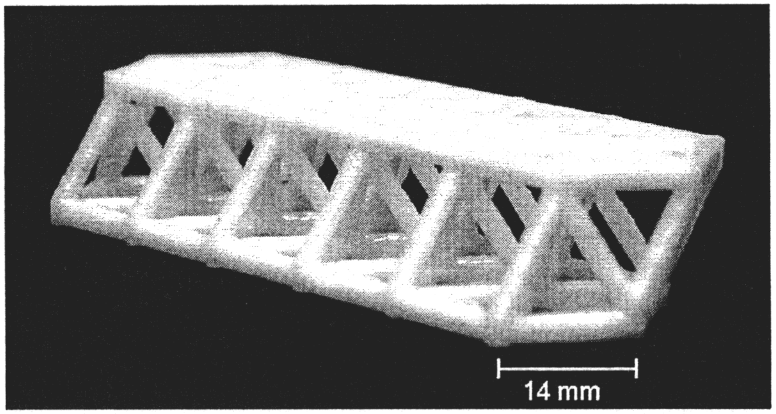
B-141



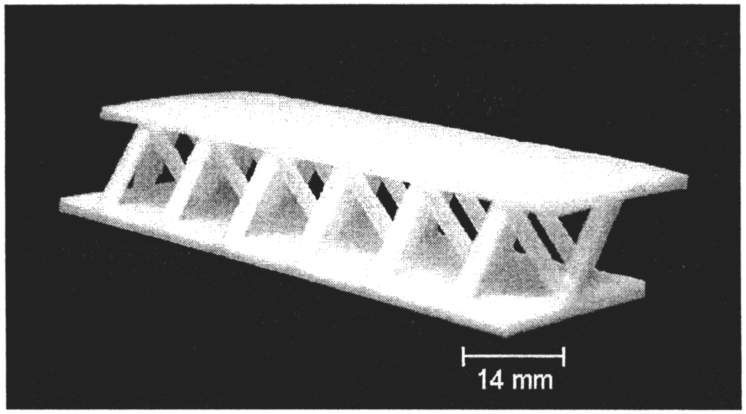
- CAD file of 3-D model geometry in .STL format.
- QuickSlice® algorithm
- ABS, casting wax, elastomer (polyester-based), polystyrene
- Layer width 0.254 - 2.54mm
- Layer thickness 0.050 - 0.762mm
- Post process smoothing-Methyl Ethyl Ketone, Acetone, Sanding

ABS (octet truss core) Patterns

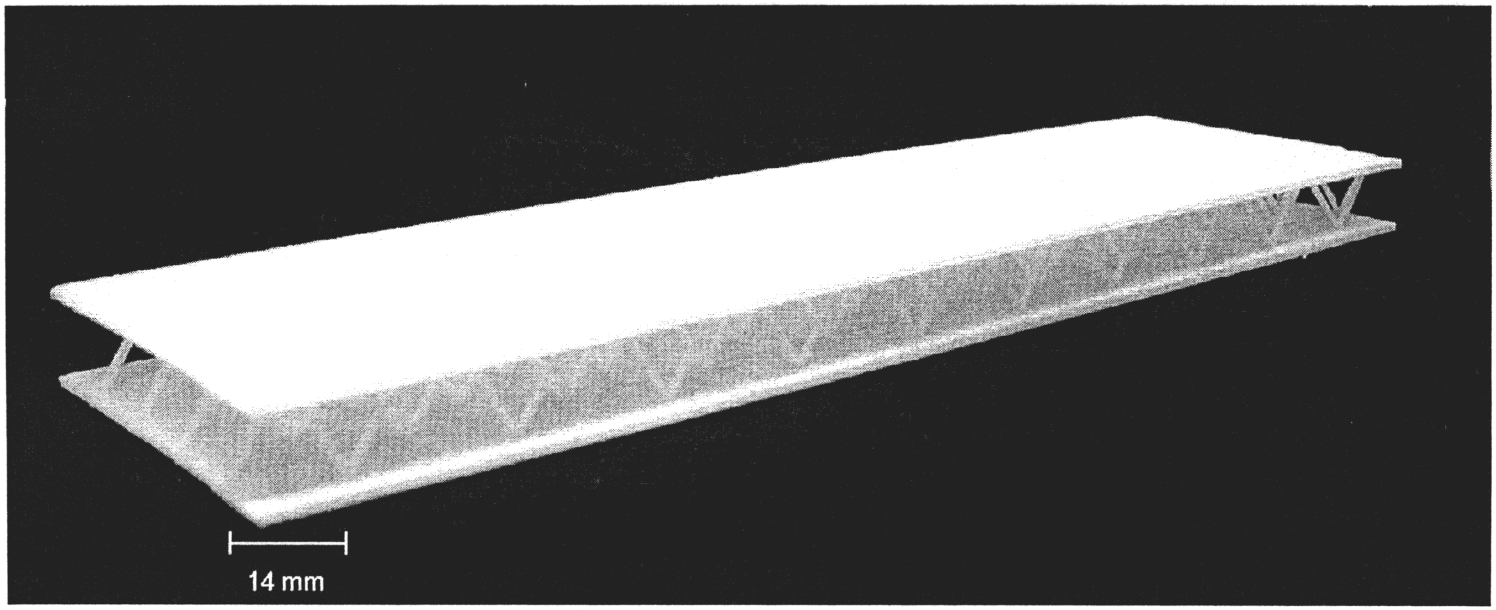
Truss Facesheets



Solid Facesheets



Wicks – Hutchinson Structure



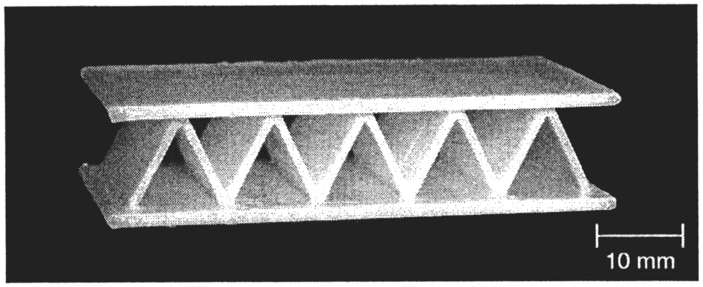
13-142

Rapid Prototyping

Fused Deposition Modeling (FDM 3000)

Pillar

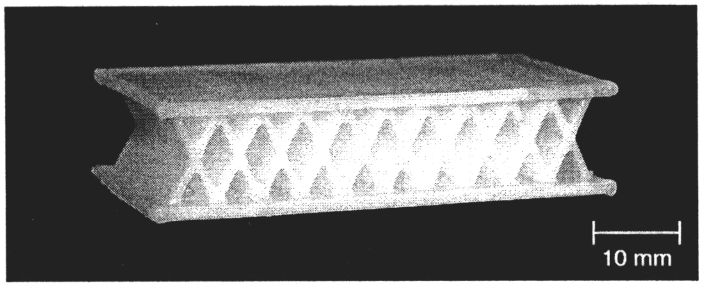
Array



B-143

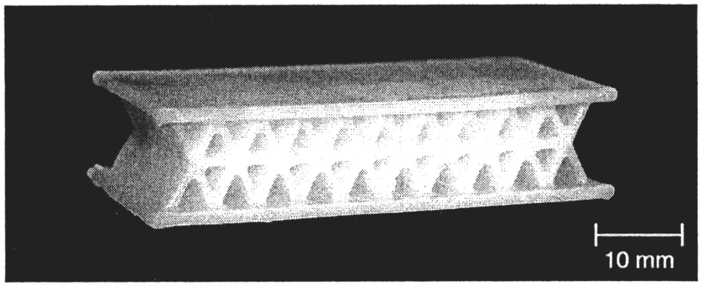
Cross Pillar

Array

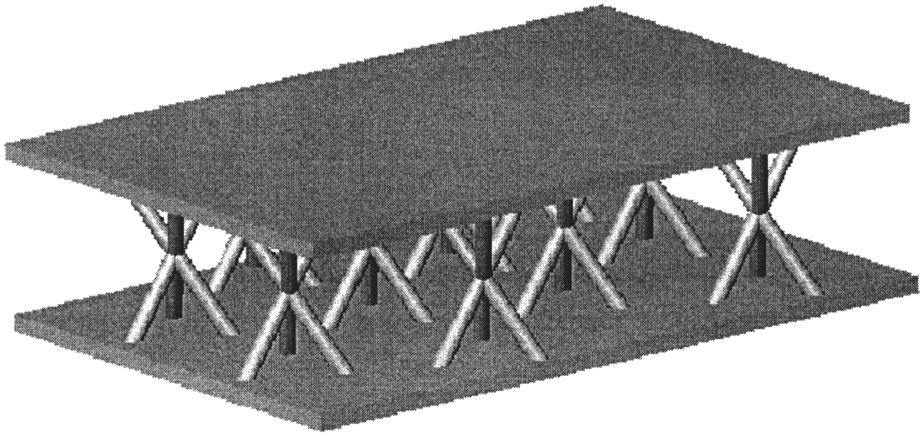


Channel

Array



Kagome Core Sandwich Panels



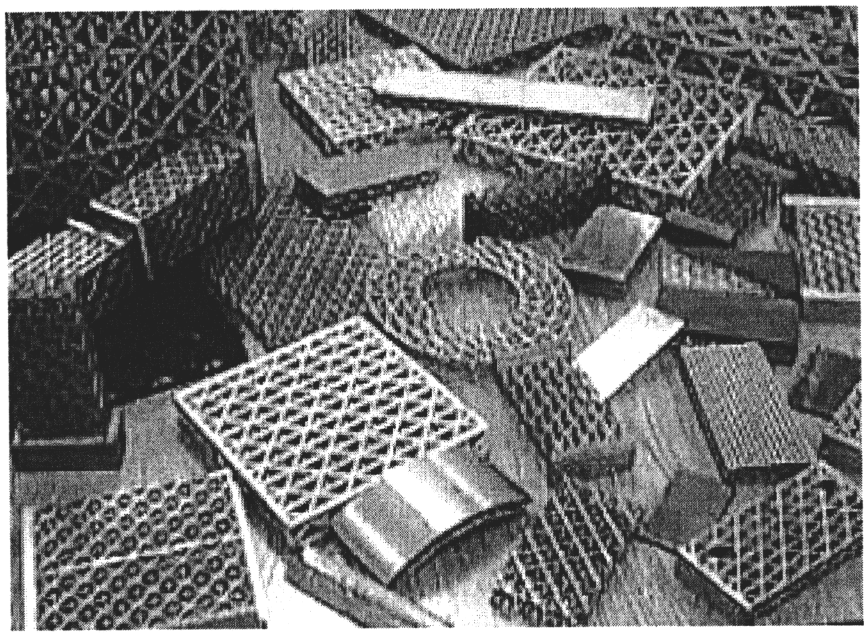
B-144

LBM – Lattice Block Materials

JAMCORP

Processing: Investment casting using injection molded templates.

Applications: Automobile, naval, and aerospace components, building structures, furniture and sporting goods.



Cell Size: 5-50mm **ρ/ρ_s: 5-15%**

Issues: Cast ability of large panels, casting factor knock-down, limited set of alloys, cost.

B-145

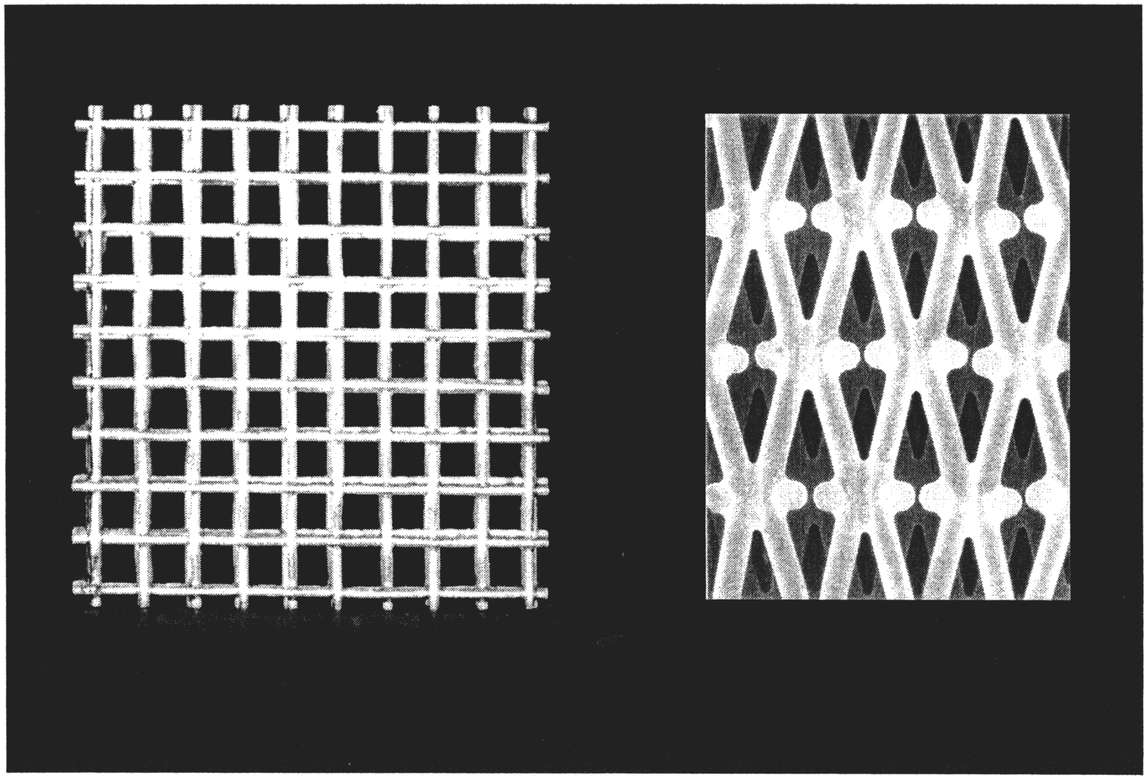
Woven Micro Truss

University of Virginia (Sypeck/Wadley)

Process: plain metal weave lay up/transient liquid phase bonding

Materials: aluminum 6061, copper alloys, Inconel, Ni-base superalloys, Ti-6Al, austenitic stainless steels,……

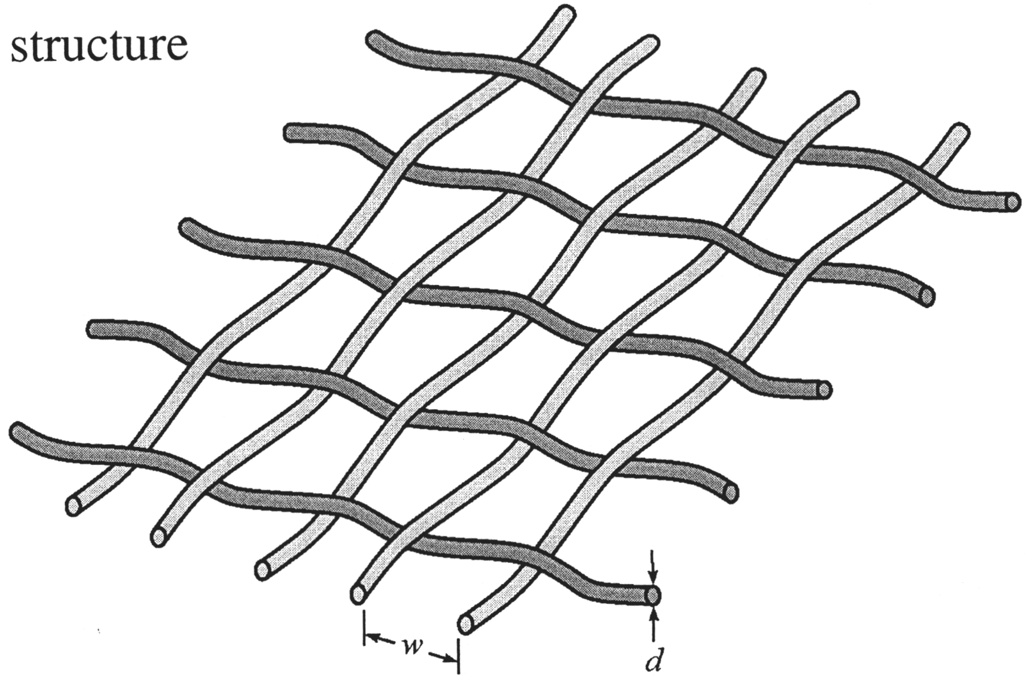
B-146



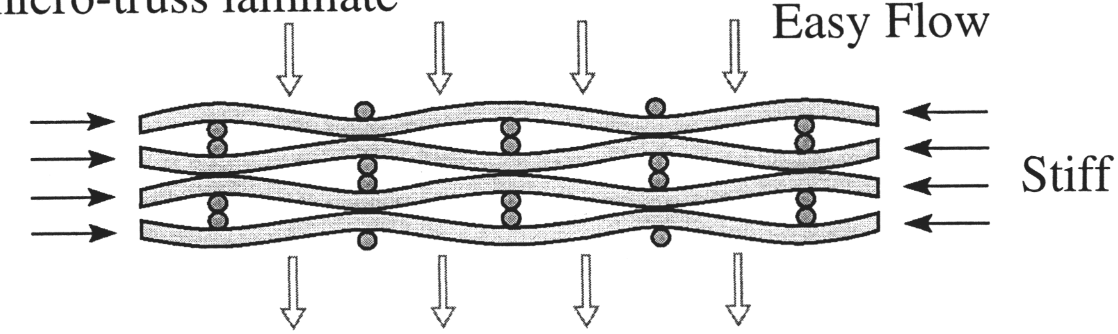
Availability: 1-50 pores per inch **ρ/ρ_s: <0.2**

Lamination Construction

a) 2D woven metal structure



b) Woven metal micro-truss laminate

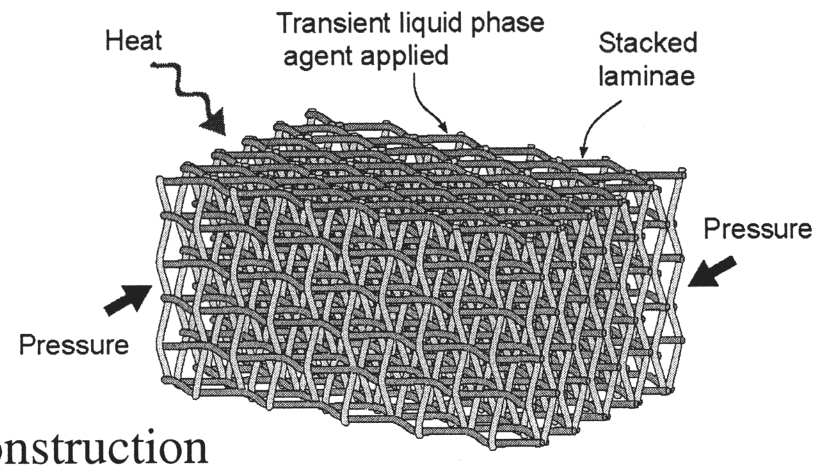


$\rho/\rho_s \approx \pi \mathbf{d/4(w+d)}$ $\mathbf{E/E_s} \approx \mathbf{0.5}\rho/\rho_s$ $\sigma_c/\sigma_{ys} \approx \mathbf{0.5}\rho/\rho_s$

B-147

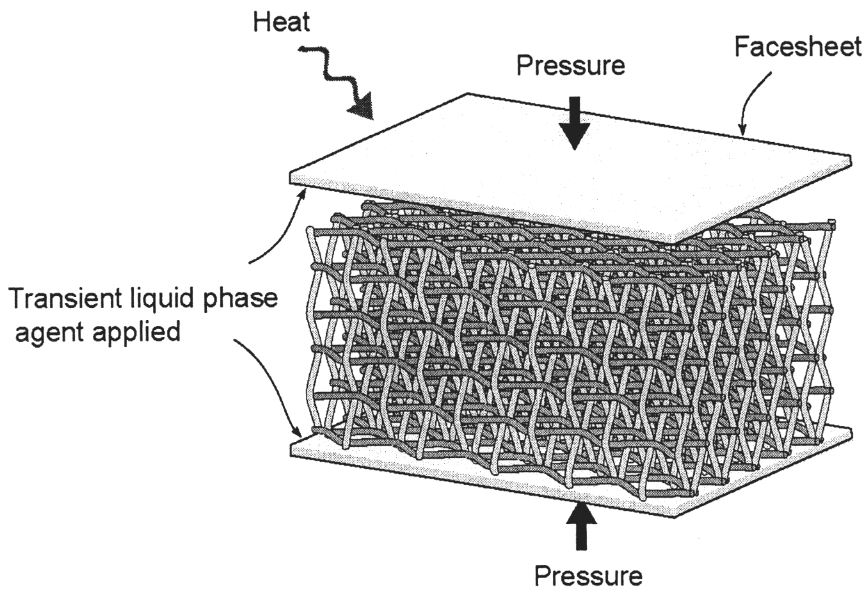
Bonding Method

a) Micro-truss laminate core construction

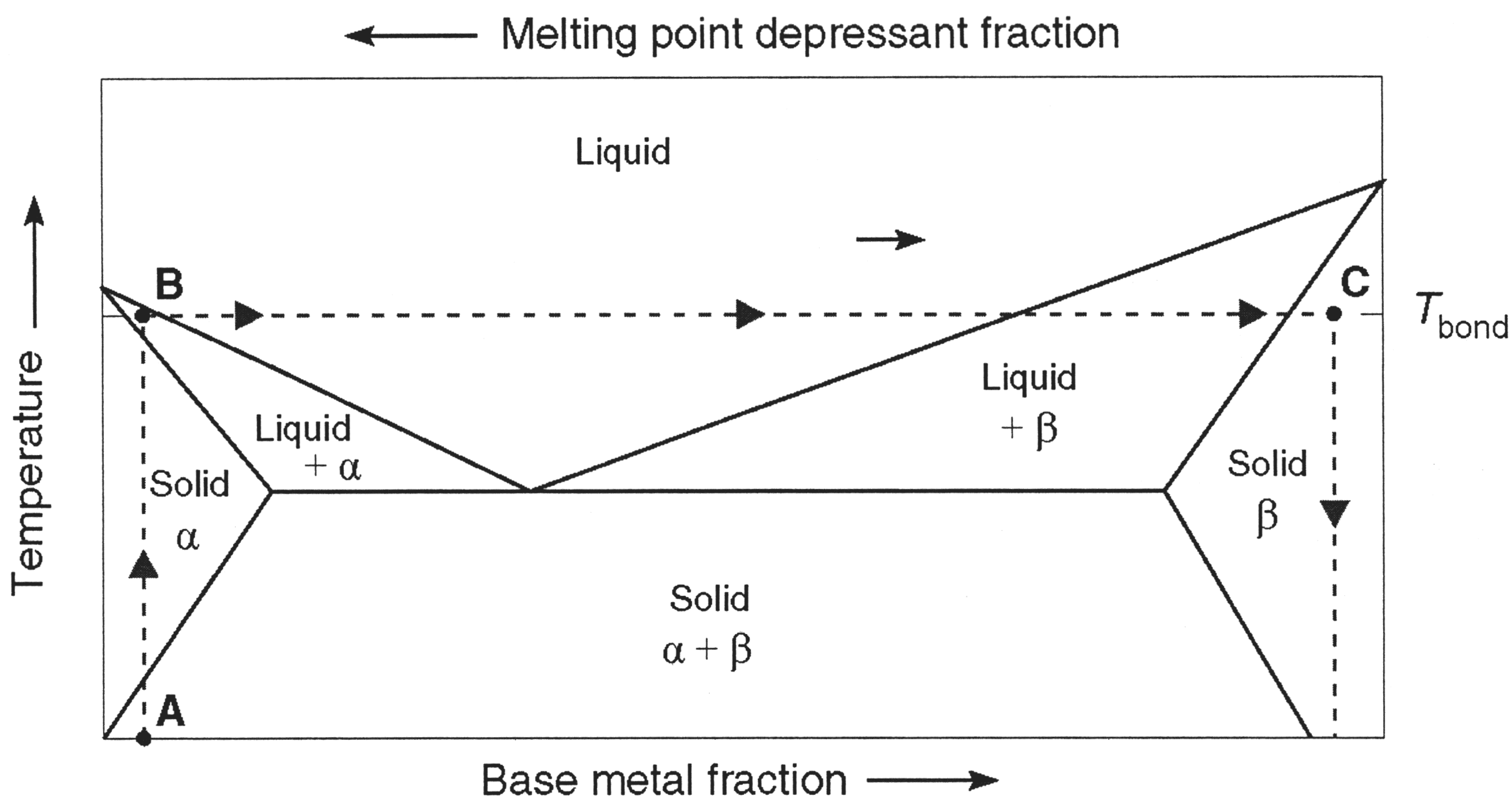


B-148

a) Sandwich panel construction



Liquid Phase Sintering

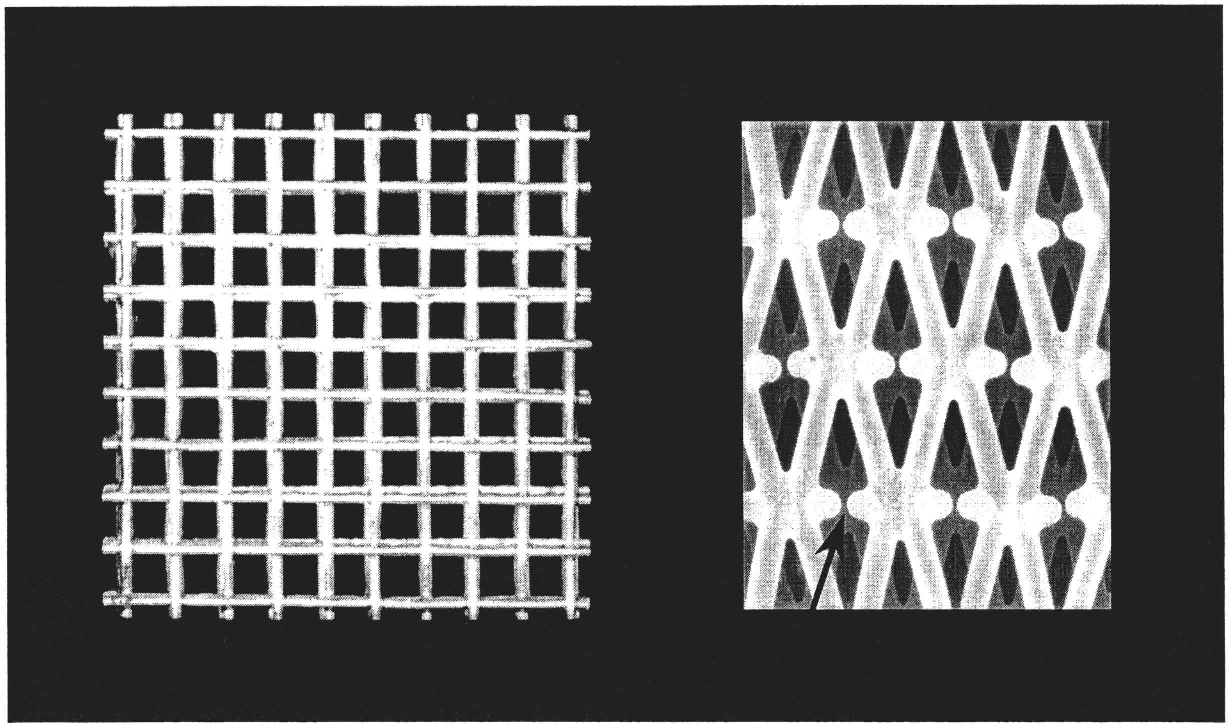


2541_liquid_phase_sinter_.ai h wadley ipm 6/2000

B-144

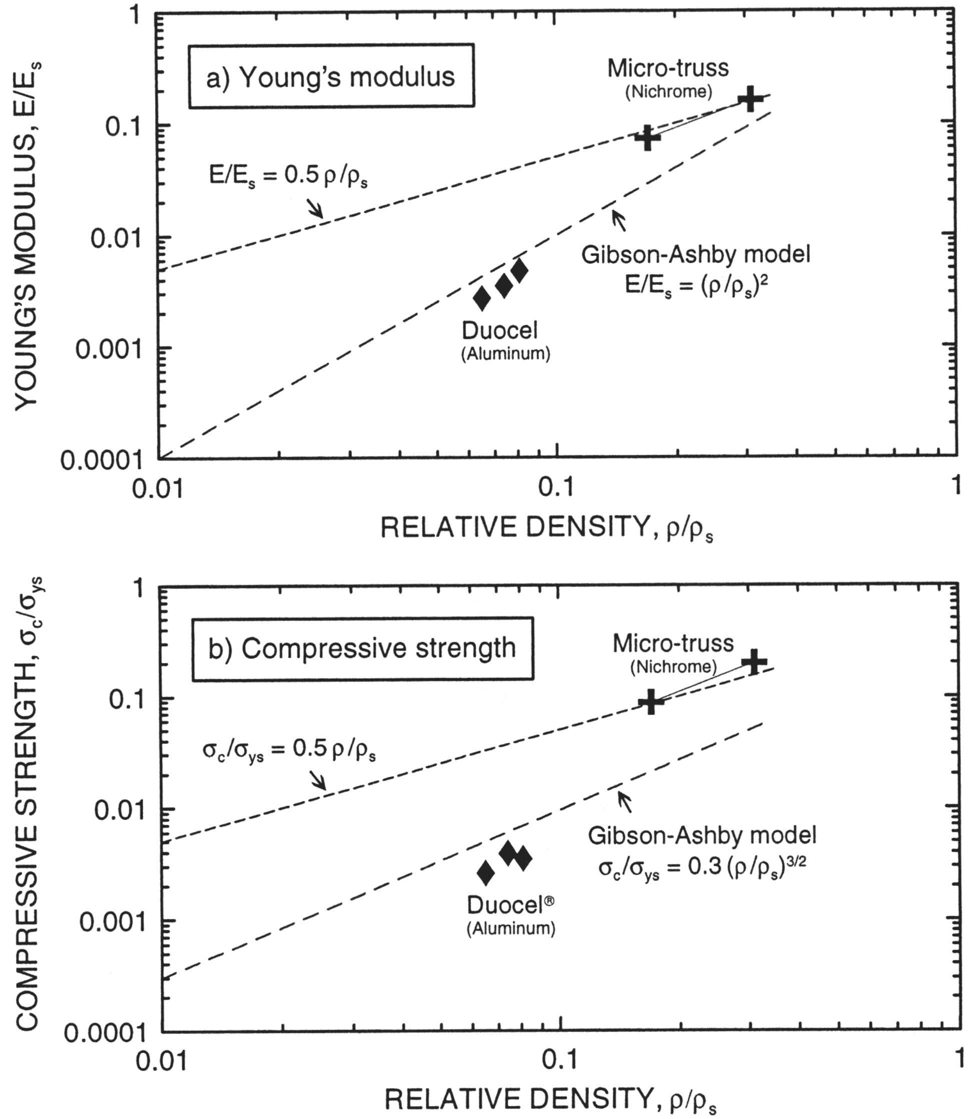
Multifunctional Micro-Truss Laminate (nichrome)

Easy Fluid Flow Excellent Load Support



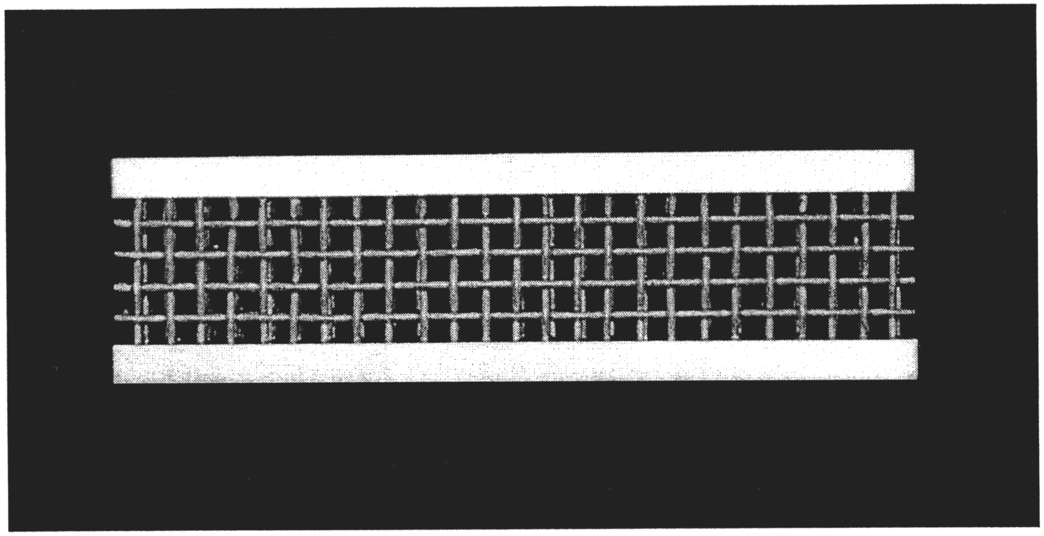
Compressive Mechanical Properties

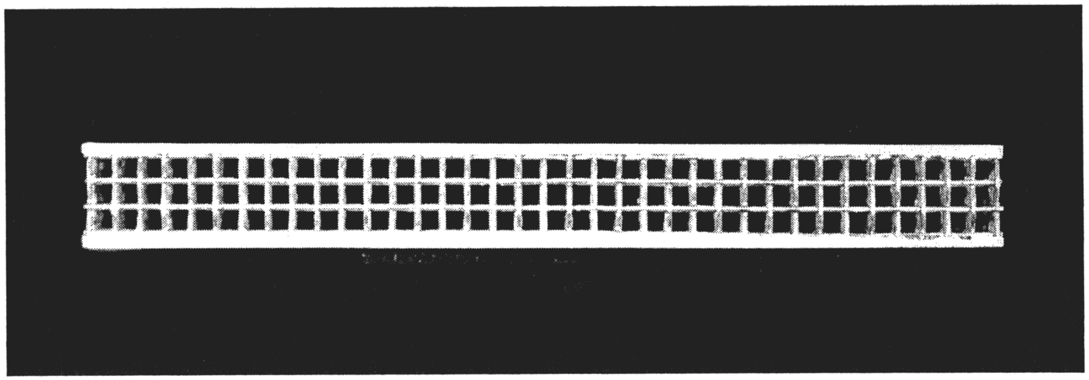
B-151



Reference: "Multifunctional Micro-Truss Laminates: Textiles Synthesis and Properties", D. Sypeck and H.N.G. Wadley, Journal of Materials Research, Vol. 16, No. 3 (2001).

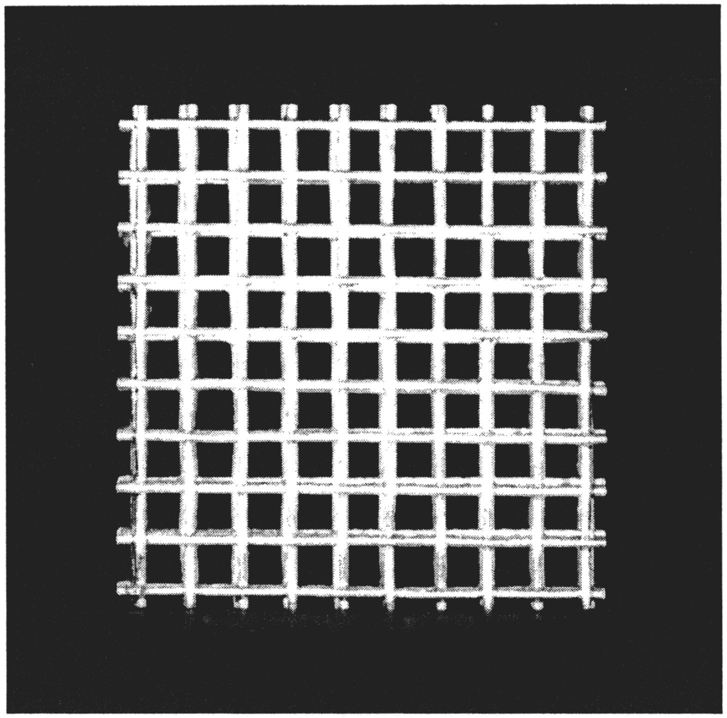
Materials Diversification

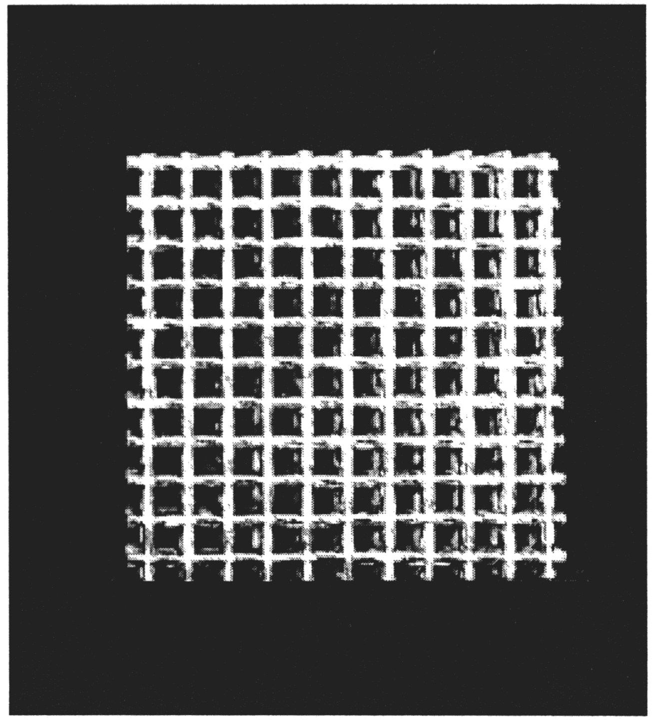




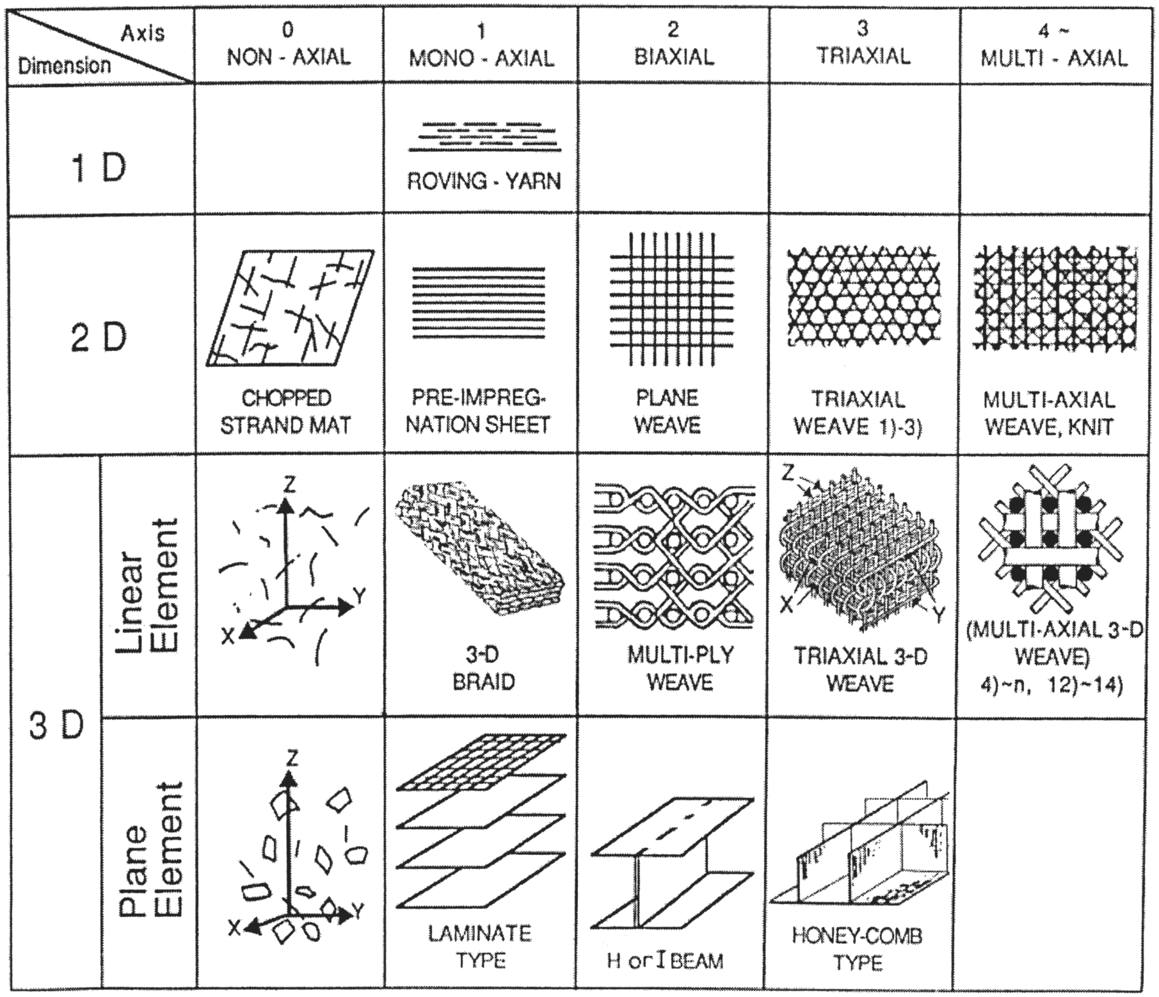
B-152

Materials Diversification





Metal Textile Can Be Made In Many Forms



B-154

REFERENCE:

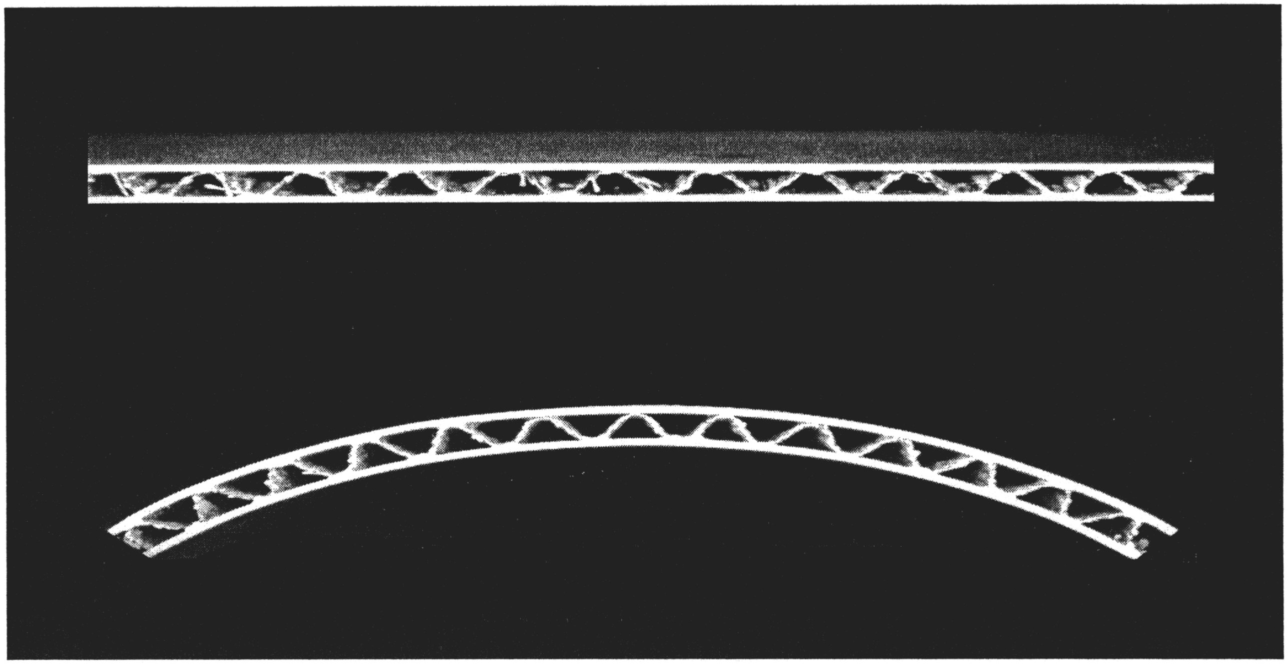
K. Fukuta, R. Onooka, E. Aoki and Y. Nagatsuka in S. Kawabata (Ed.), 15th Text. Res. Symp., The Textile Machinery Society of Japan, Osaka, 1984, pp. 36-38.

F.K. Ko, “Three Dimensional Fabrics for Composites”, In Textile Structural Composites, edited by T.-W. Chou and F.K. Ko, pp.129-171, Elsevier, 1989.

Sandwich Panel Wingskin

For efficient support of bending and twisting loads:

- Space two stiff, strong skins far apart.
- The lightest core that still supports the necessary compressive and shear loads.
- Skins that are well bonded to the core.



304 stainless steel
Core relative density: 0.04
Facesheet thickness: 0.61 mm

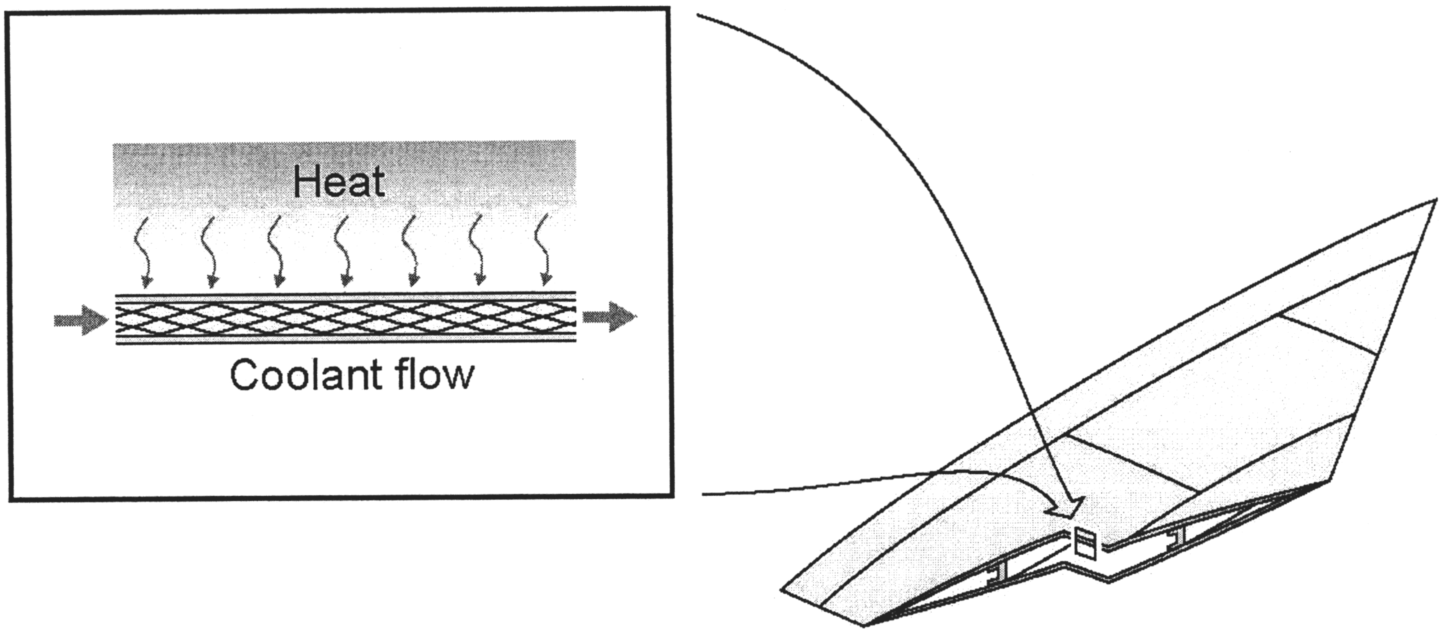
Advantages:

- High fluid permeability, complex shapes, dent rather than crack, many materials choices, relatively inexpensive ($11.64/ft^2).
- Steel and Nickel alloys. Aluminum and titanium appear feasible.

B-155

Supersonic Airfoil Issues

Open Cell Metal Core Sandwich Panel Wingskins



B-156

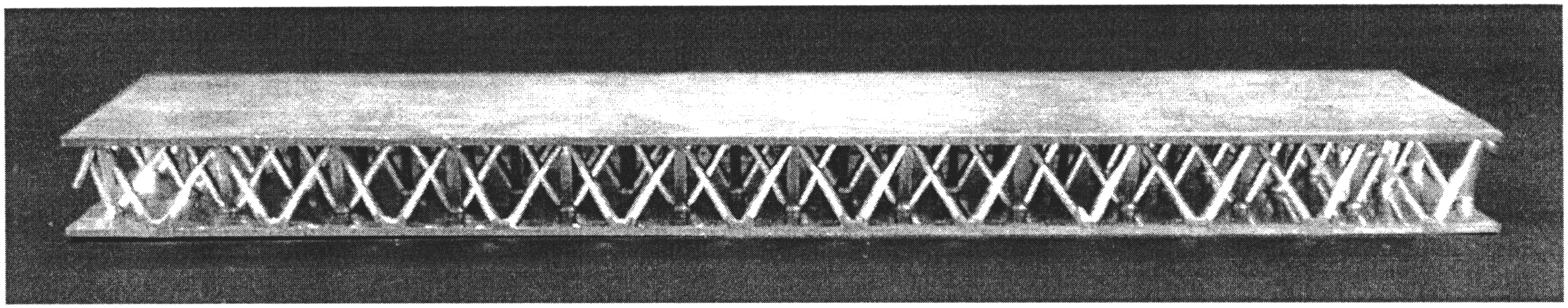
Constructed Cellular Metals

University of Virginia (Sypeck/Wadley)

Process: pressing of expanded/perforated metal + transient liquid phase bonding

Materials: aluminum 6061, stainless steels, titanium alloys, Ni-Base superalloys, copper alloys (ductile materials).

B-157

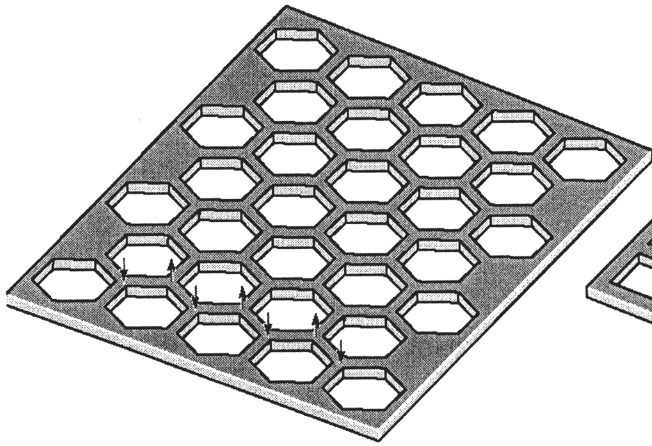


Cell Size: 2-50mm ρ/ρ_s**: 1-10%**

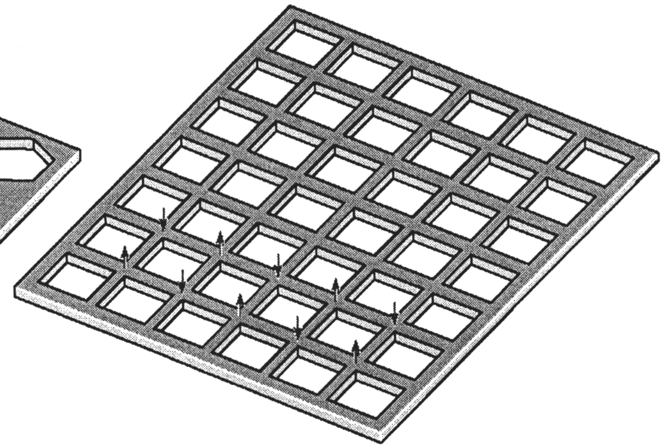
Periodic Truss Cores

13-158

Hexagonal perforated sheet

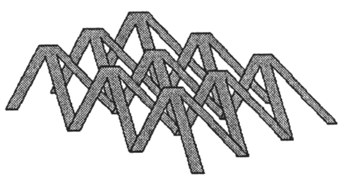


Square perforated sheet



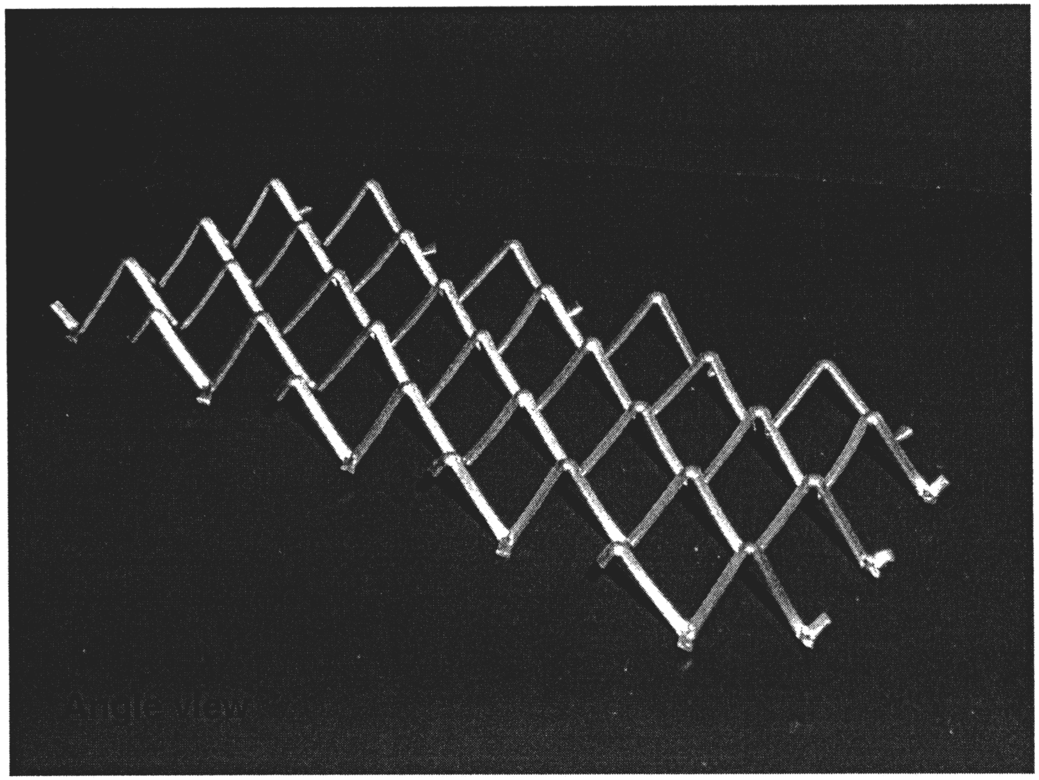
Intersections to be shaped out of plane

Tetrahedron Truss



Pyramidal Truss

Wrought Stainless Steel Tetrahedral Truss



Material: 304 stainless steel
Tetrahedron height: ~9 mm
Relative density: ~2%

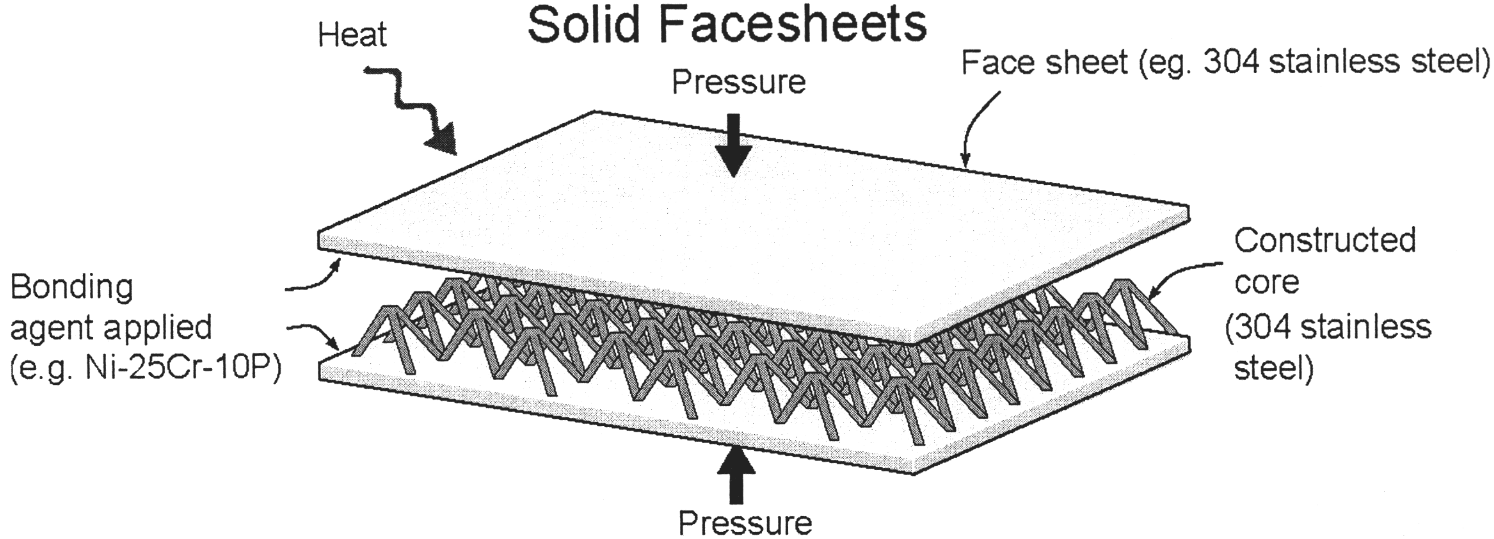
Leg width: ~1.25 mm
Leg thickness: ~0.57 mm

Other Materials: Al alloys (6061, 6951, 3003, 1100), titanium alloys, copper, nickel alloys, . . .

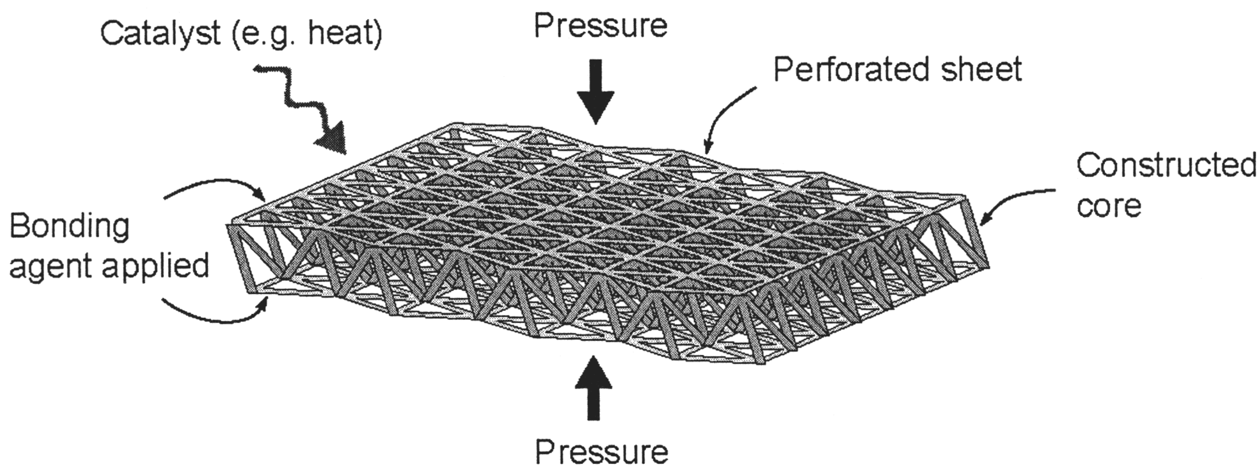
13-159

Sandwich Panel Construction Techniques

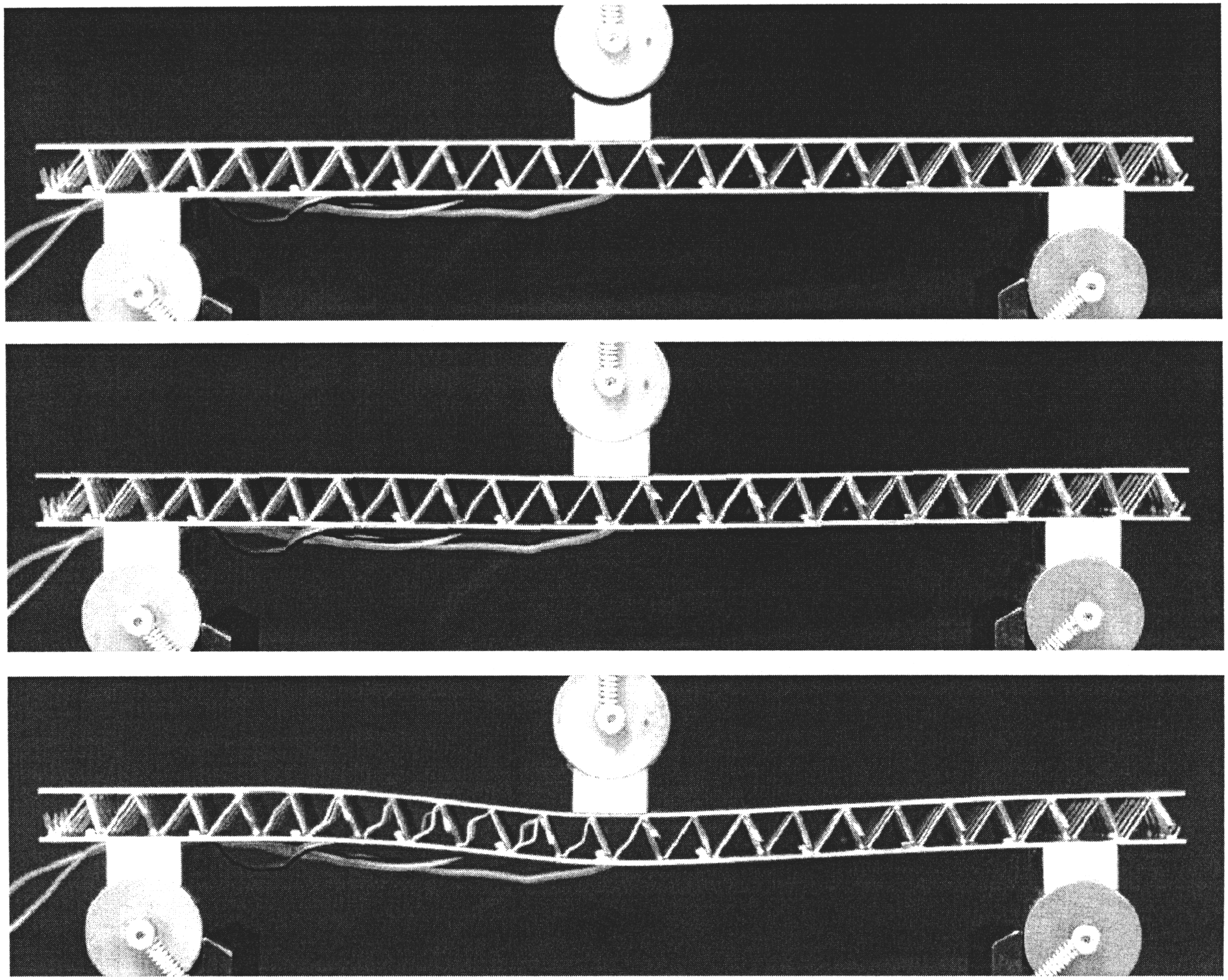
Solid Facesheets



Expanded Facesheets

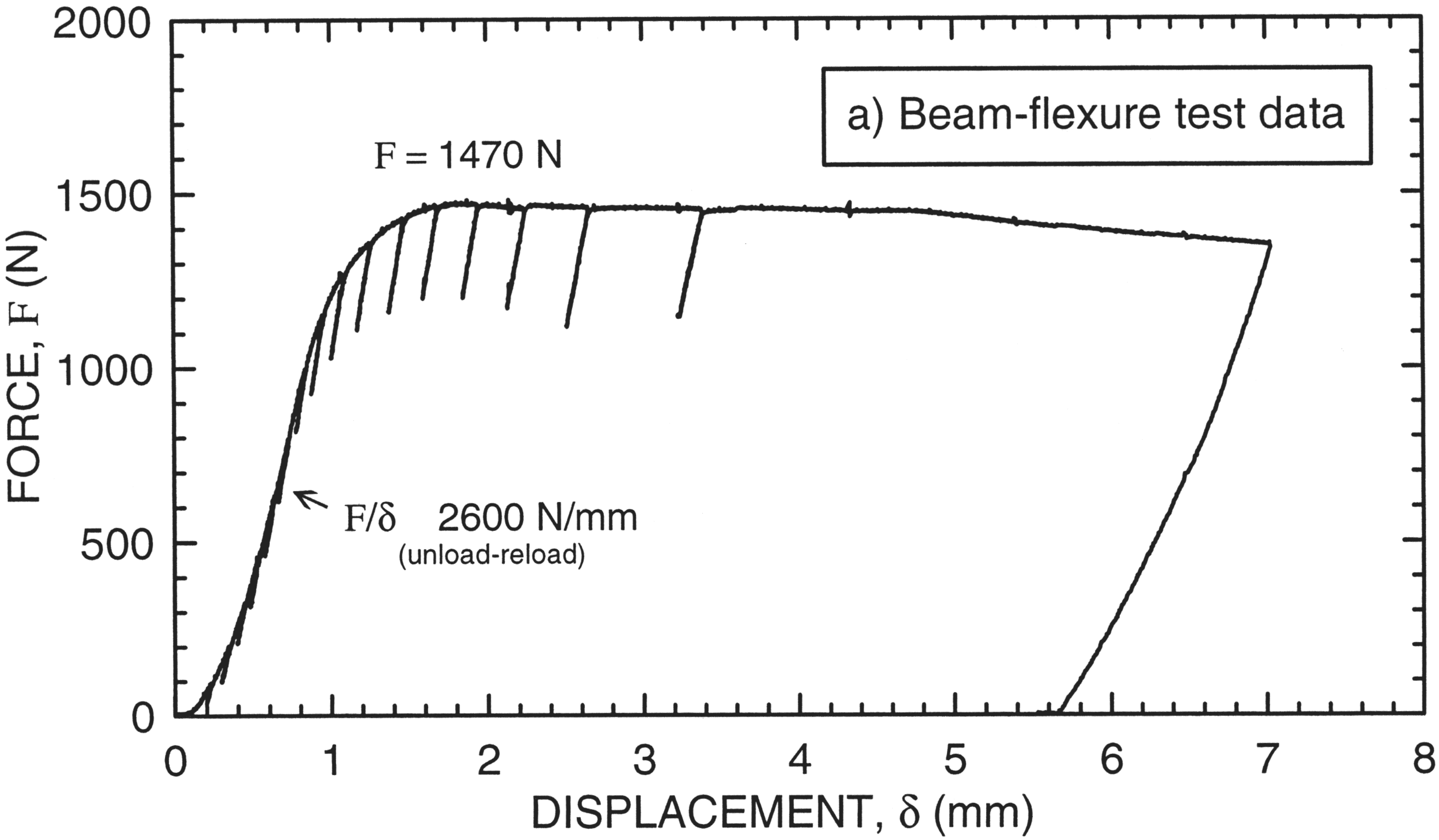


Constructed Truss Structure Failure Mechanisms



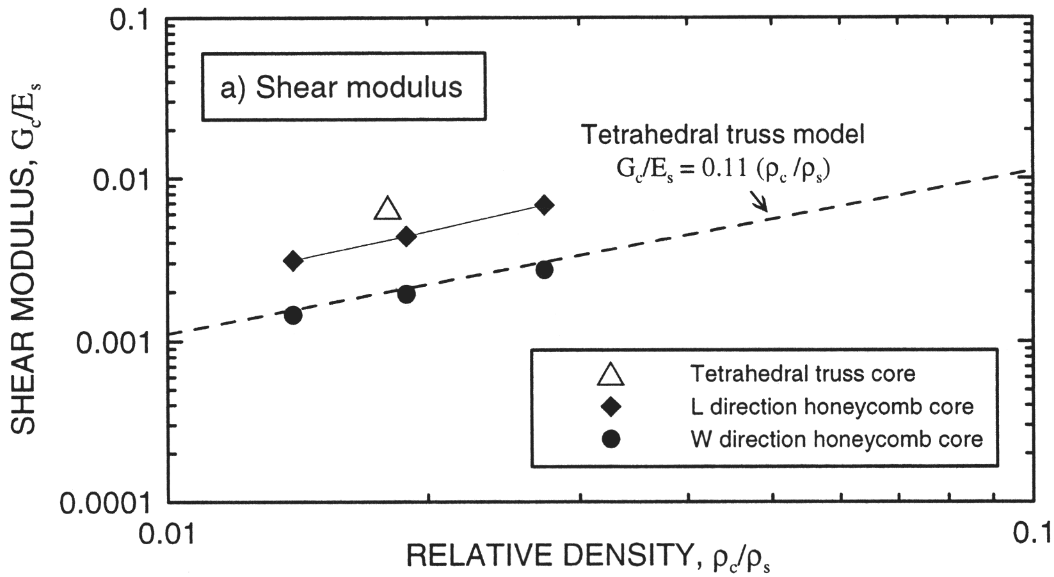
B-161

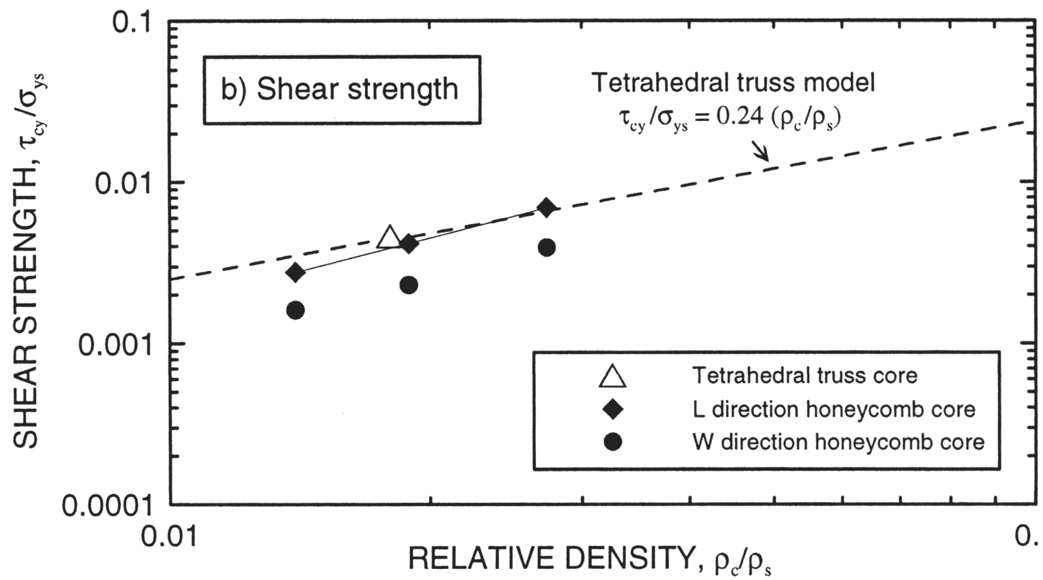
Constructed Cellular Solid Load Response:
3-Point Bending



B-162

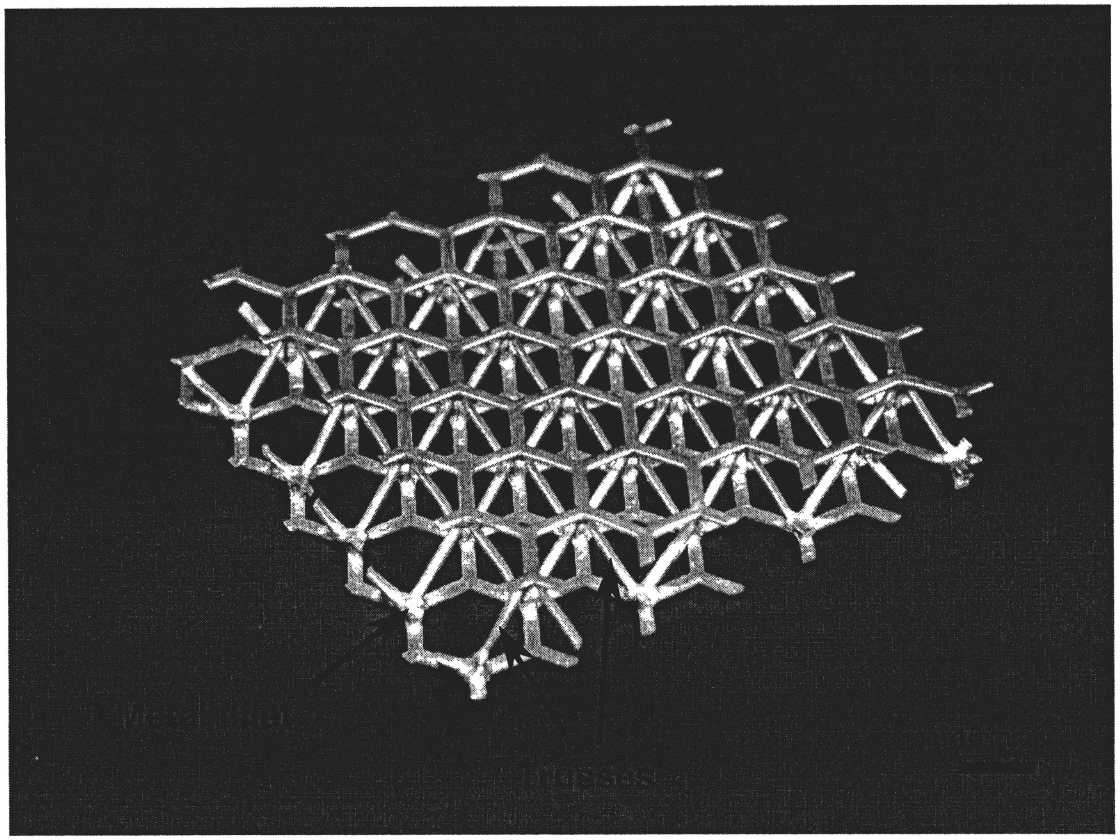
Constructed Cellular Solid Property Comparisons





B-163

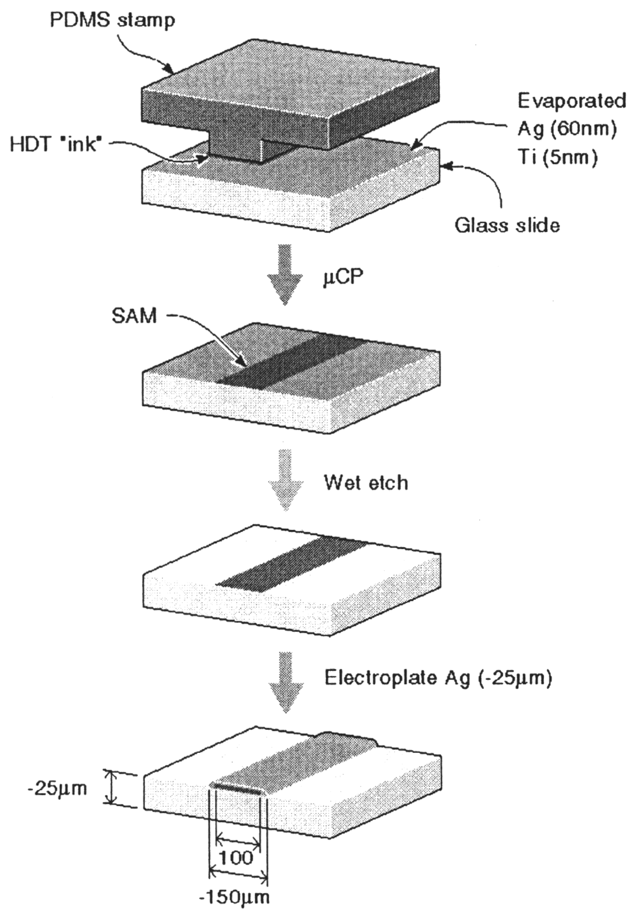
Tetrahedral Truss Core / Hexagonal Facesheets



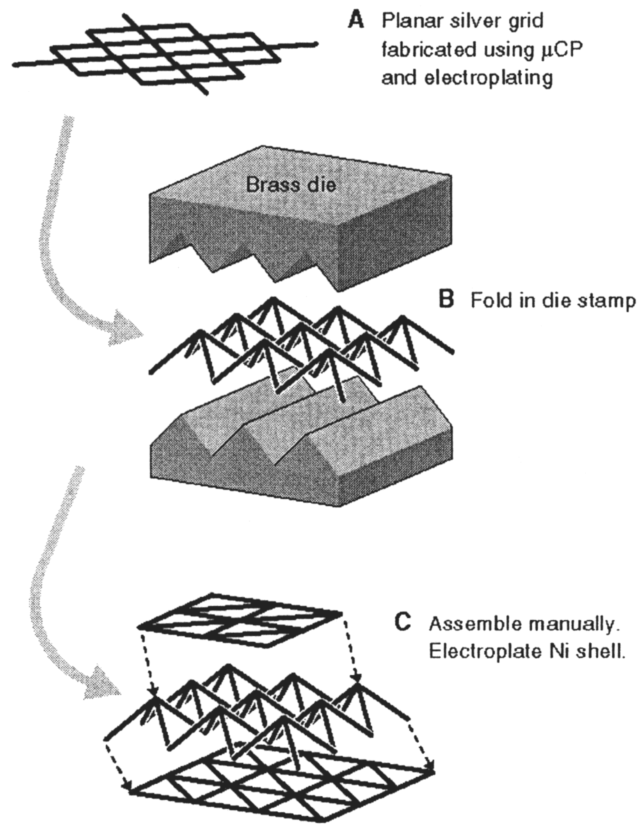
B-164

Electro-Deposited Truss Structures

Microcontact Printing (µCP)



Truss Pressing / Assembly



Electrodeposition bonding creates truss structure.

B-165

2582_electrodeposit_truss_.ai h wadley ipm 6/2001

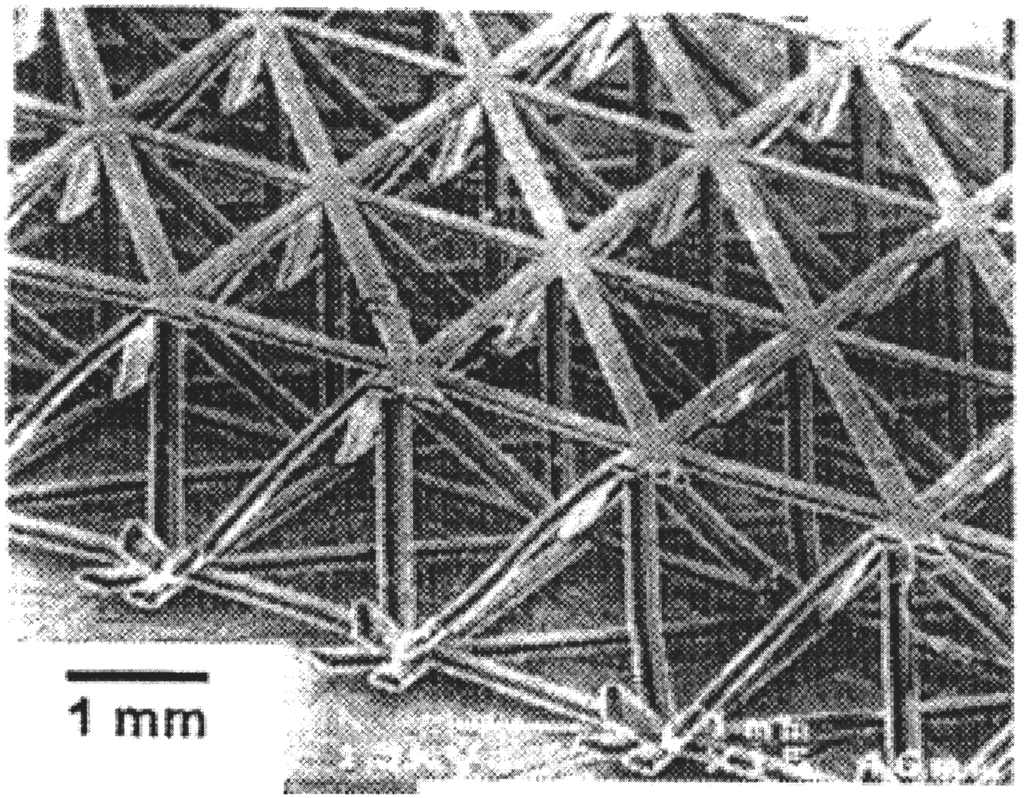
Britain, Sugimura, Schueller, Evans and Whitesides, J. Microectromechanical Systems, 10 (1), March 2001, 113

Electro-Deposited Microtruss Structures

Harvard (Whitesides, Britain, Sugimura, Schueller, Evans)

Process: soft lithography (MCP), Electrodeposition

Materials: Copper, Nickel

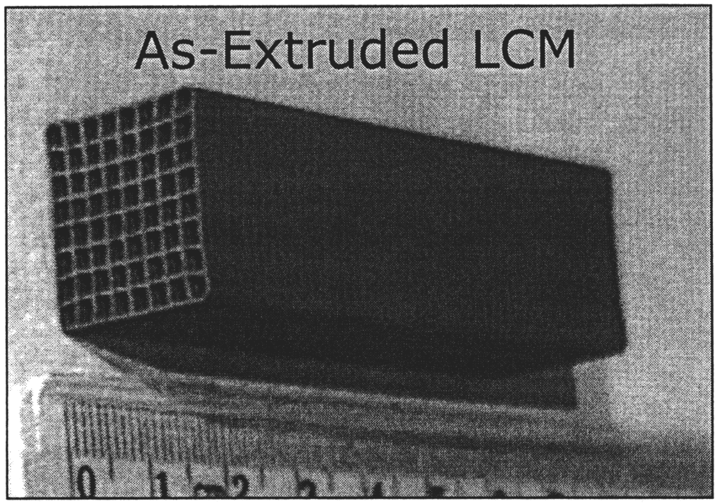


B-166

Prismatic Cellular Metals

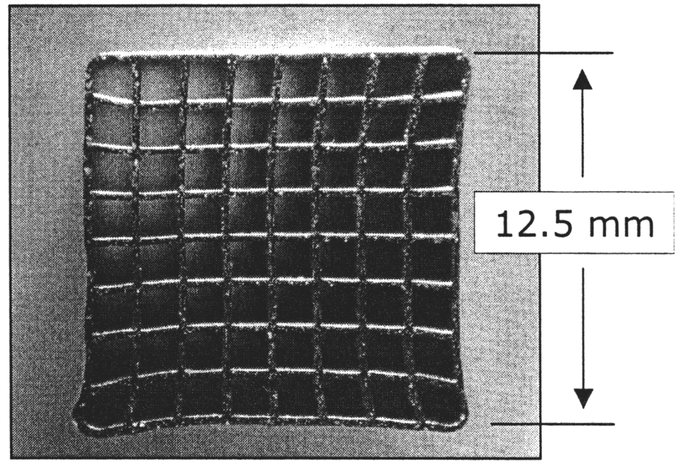
B-167

Extrusion of Metal Precursors

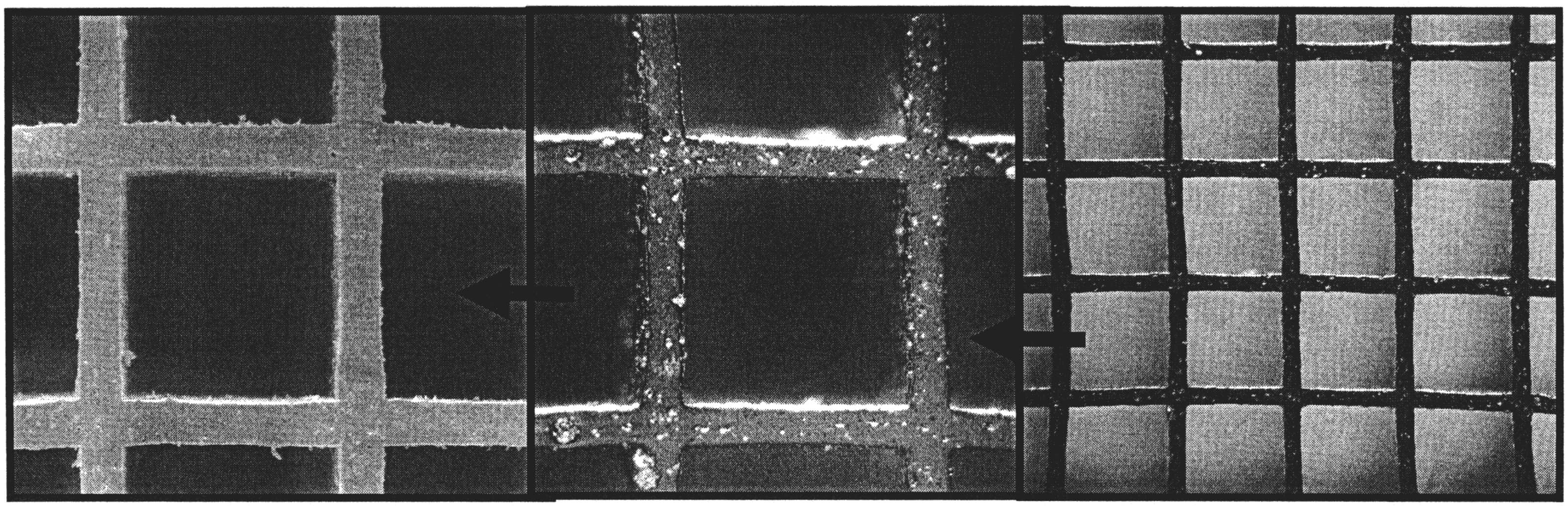


Reduction

& Sintering



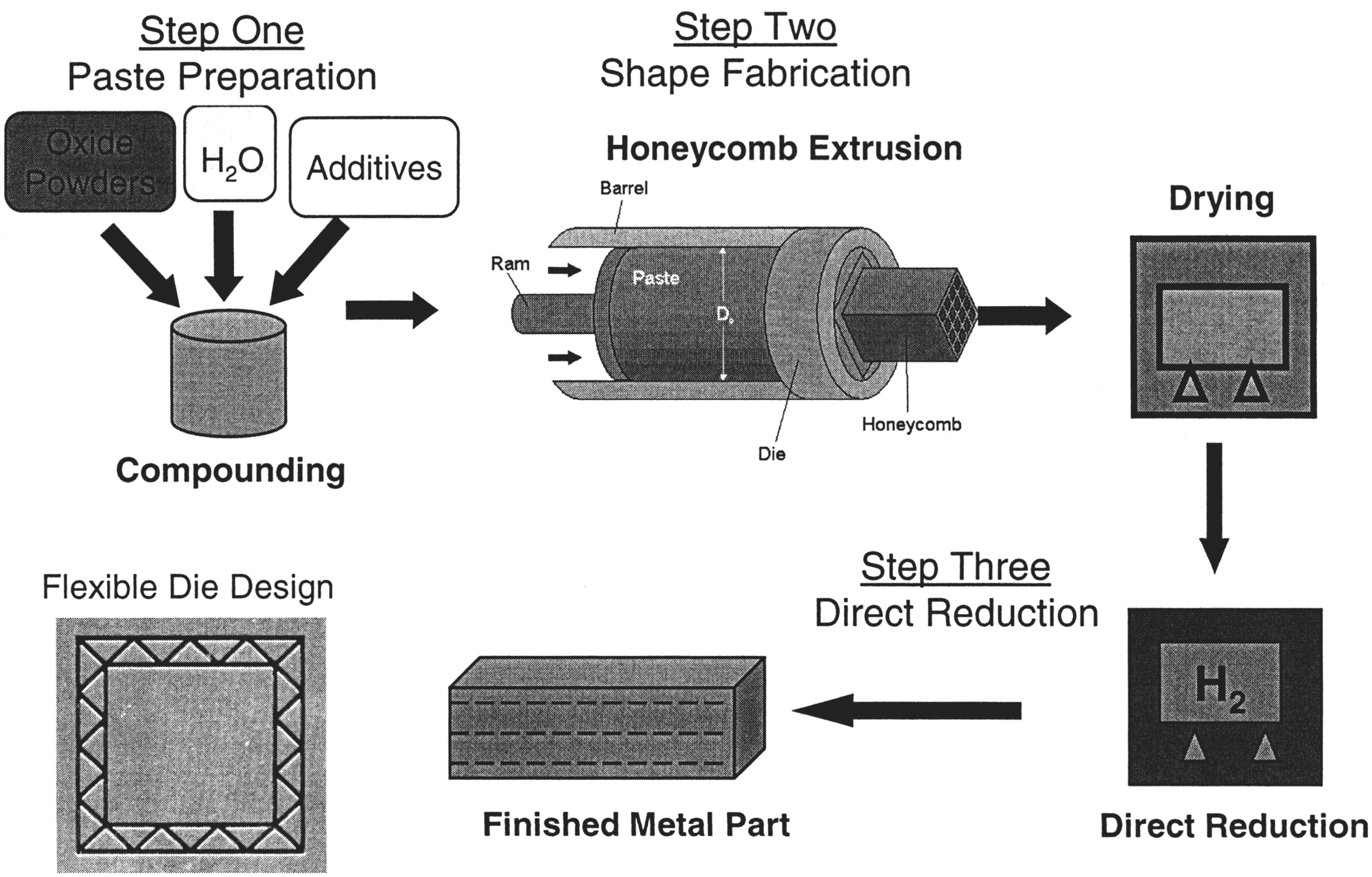
B-168



SEM Micrograph | Front Lighting | Back Lighting

Georgia Institute
of Technology

Oxide Powders Transformed into Metal Linear Cell Structures



13-169

LinCelloy

Georgia Institute of Technology

Material Compositions

Maraging Steels

Fe 18Ni 12Co 4Mo 1.5 Ti

from Fe_3O_4, NiO, Co_3O_4, MoO_3, TiH_2

Reduction = Hydrogen at 1350 °C

- **Ni Alloy - "617"**

  22Cr 55Ni 12Co 9Mo from Cr_2O_3, NiO, Co_3O_4, MoO_3

- **Copper**

  Cu, Cu 1Ni, Cu 3Ni, Cu 8Ni, Cu 3Ag from Cu_2O, NiO, AgO

- **Inconel reduction process ("718") ***

$$68NiO + 27.8Cr_2O_3 + 25.7Fe_2O_3 + 7.3Nb_2O_5 + 4.5MoO_3$$

$$\xrightarrow{H_2} 53.4Ni\ 19Cr\ 18Fe\ 5.1Nb\ 3Mo + 34.8H_2O$$

*Weight Ratios

B-170

Georgia Institute
of Technology

Summary

- Many methods for manufacturing cellular metals are available. They result in either stochastic or periodic cellular metals.

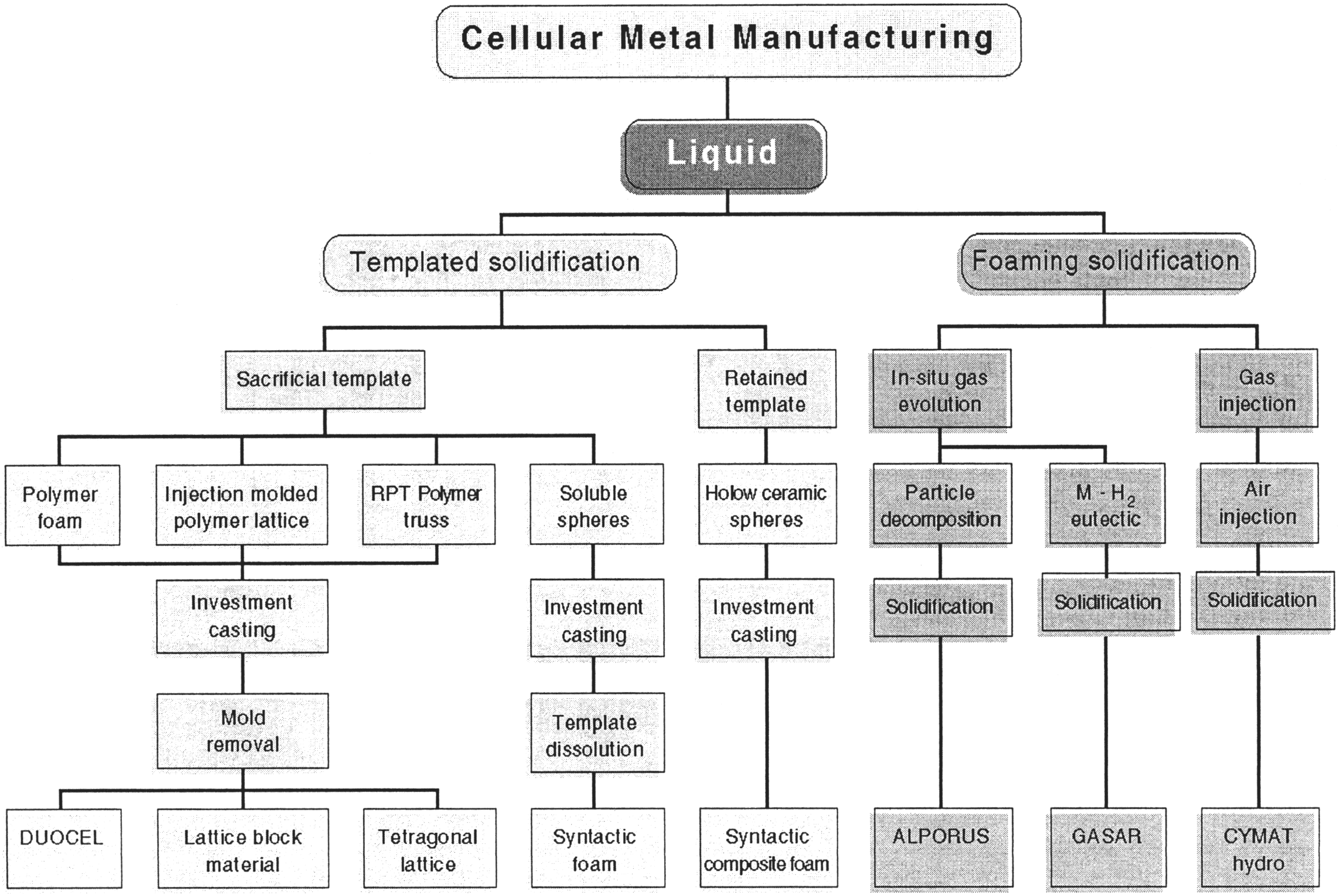
- The properties of cellular metals depend upon the (structure/properties) of the material in the ligaments AND the metal topology. Foaming processes lead to inefficient load supporting topologies. Alloy design science may improve ligament properties.

- Many methods for manufacturing periodic cellular metals are emerging. Some are likely to be cost competitive with foaming (much superior to Honeycomb).

- Periodic structures may be superior for sandwich panel structures and multifunctional heat exchangers.

B-171

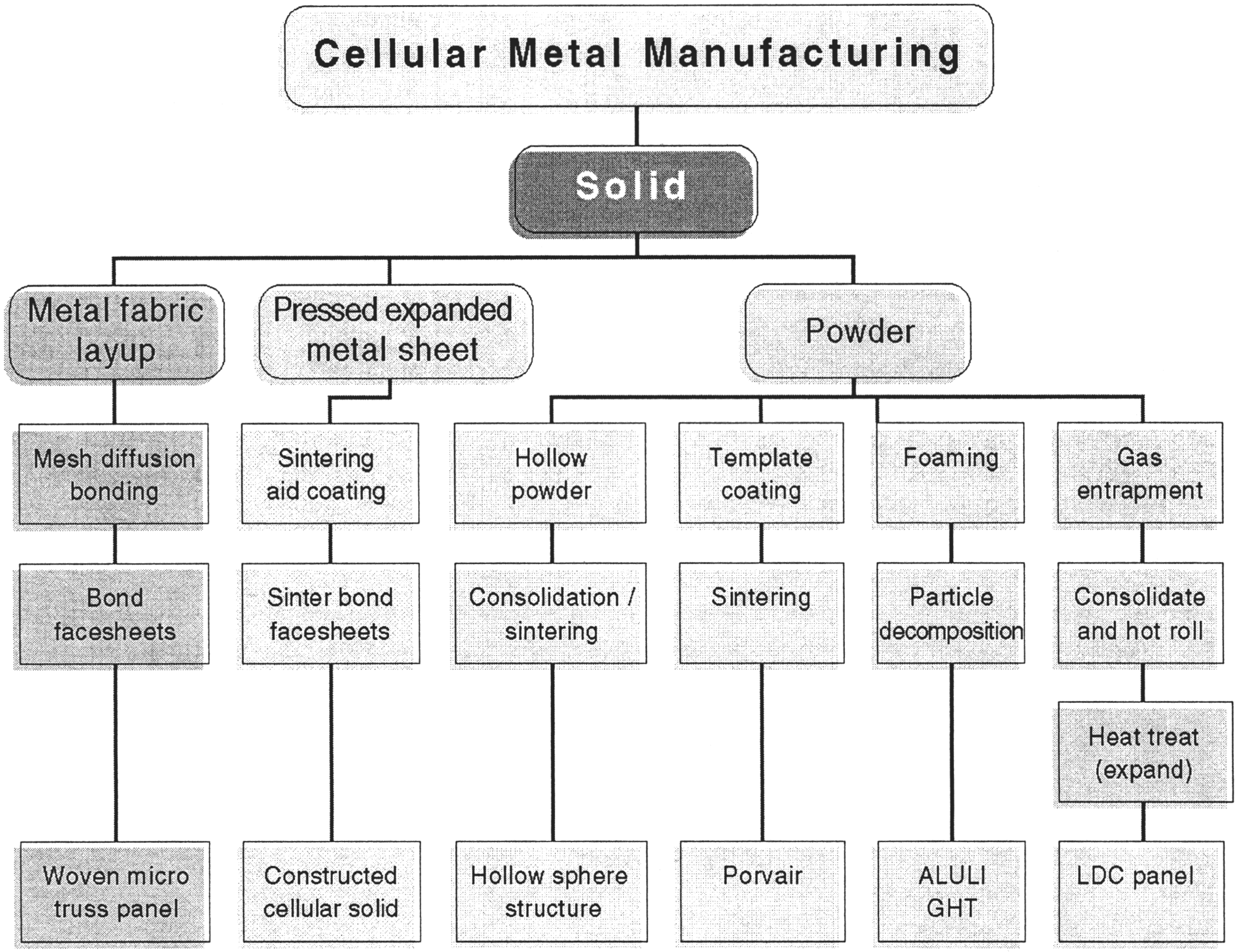
Cellular Metal Manufacturing – Liquid Route



B-172

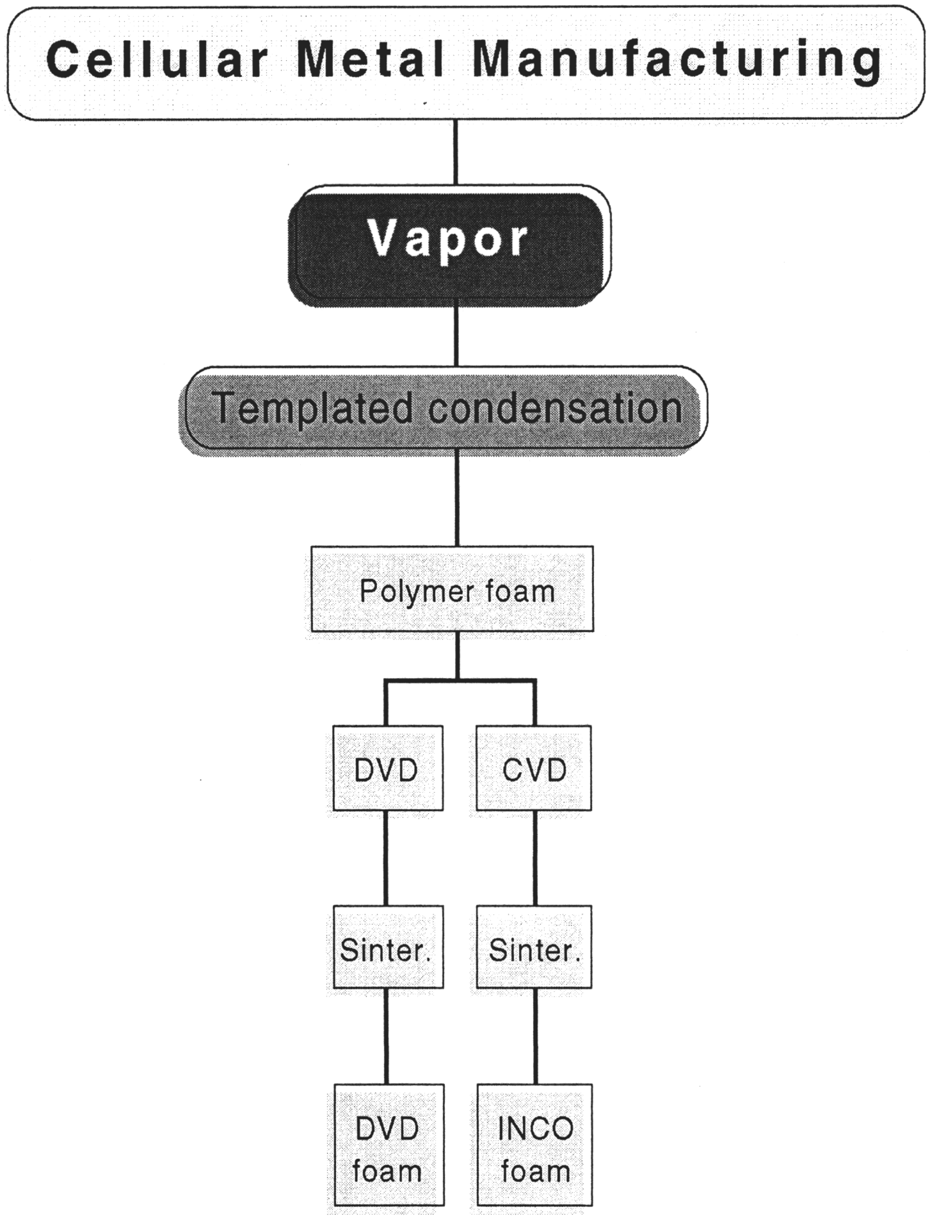
2582_cellular_liquid_.ai h wadley ipm 6/2001

Cellular Metal Manufacturing – Solid



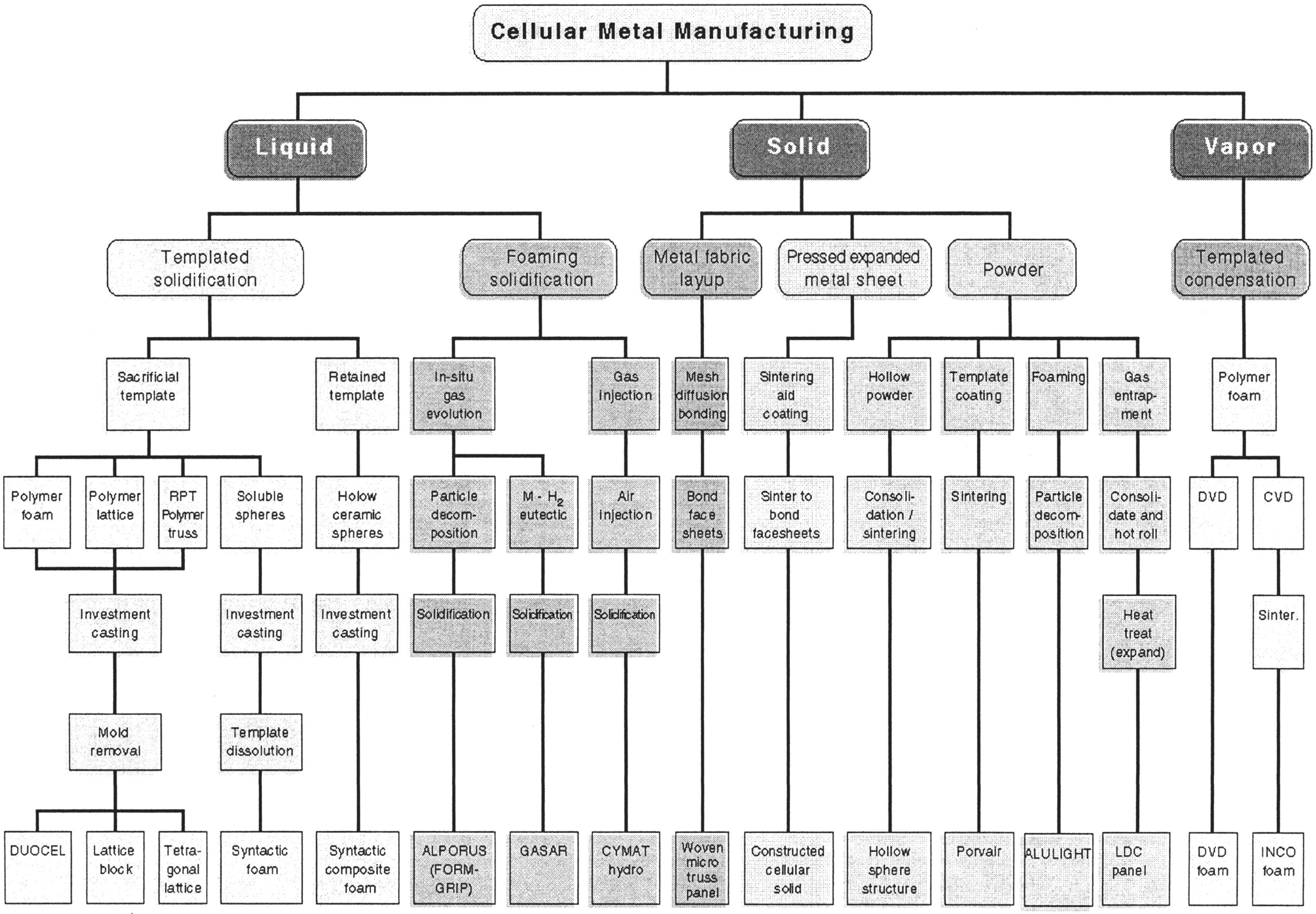
B-173

Cellular Metal Manufacturing – Vapor



B-175

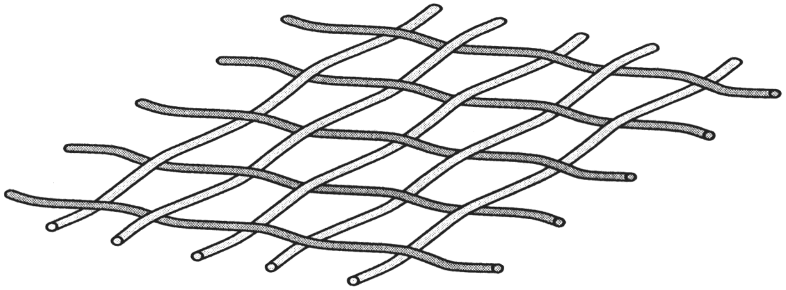
Cellular Metal Manufacturing



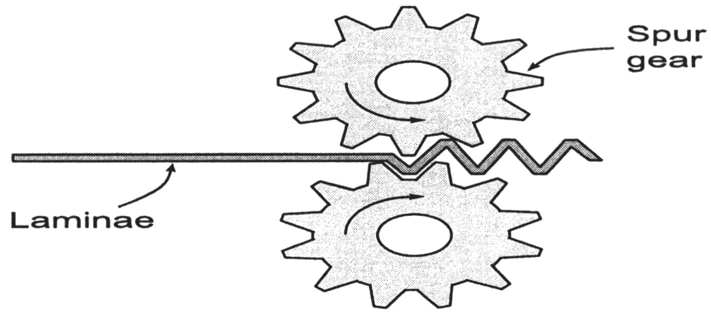
2582_cellular_manufacturing h wadley ipm 6/2001

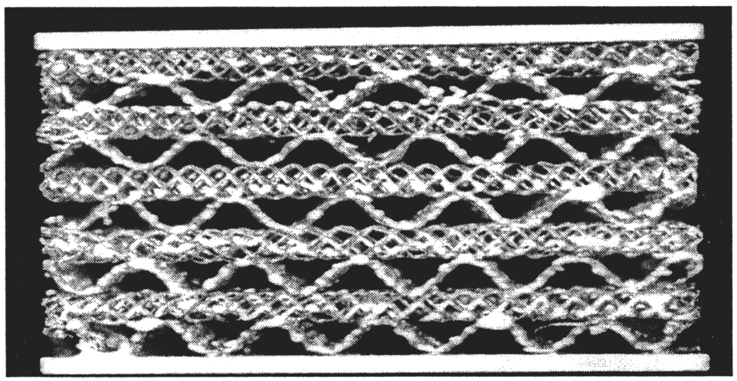
Textile-Based Methods

a) Wire mesh



b) Corrugation





B-176

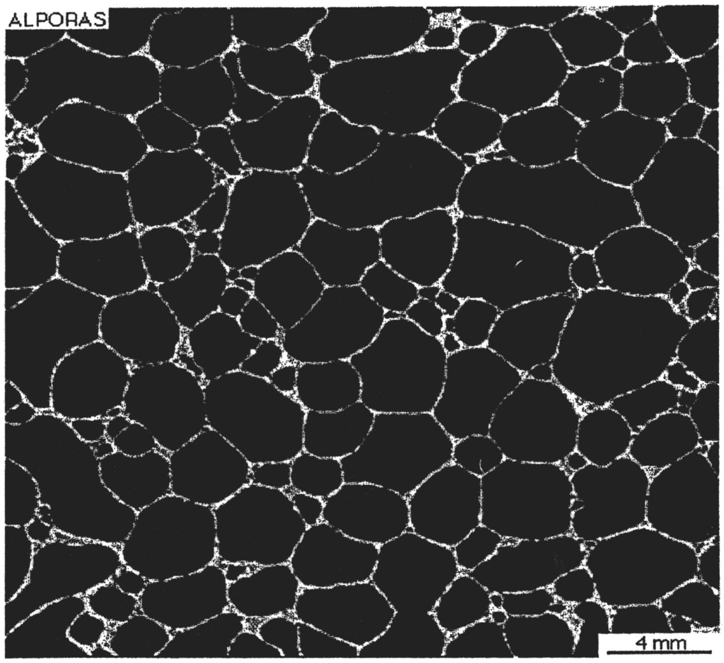
ANTHONY EVANS
PRINCETON UNIVERSITY
PRINCETON MATERIALS INSTITUTE

DESIGNING WITH MATERIALS

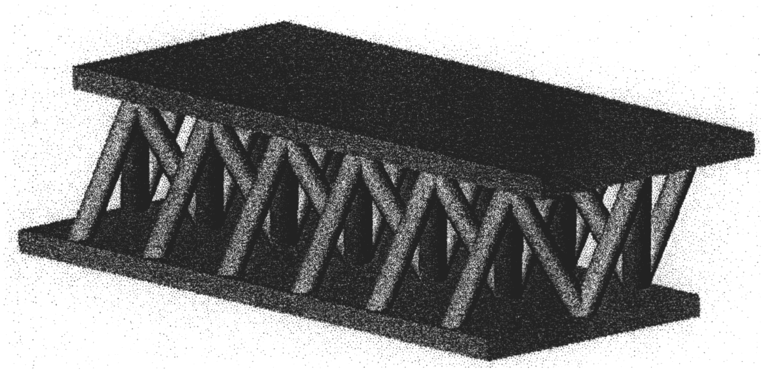
B-177

TWO CATEGORIES OF TOPOLOGY

Stochastic



Periodic



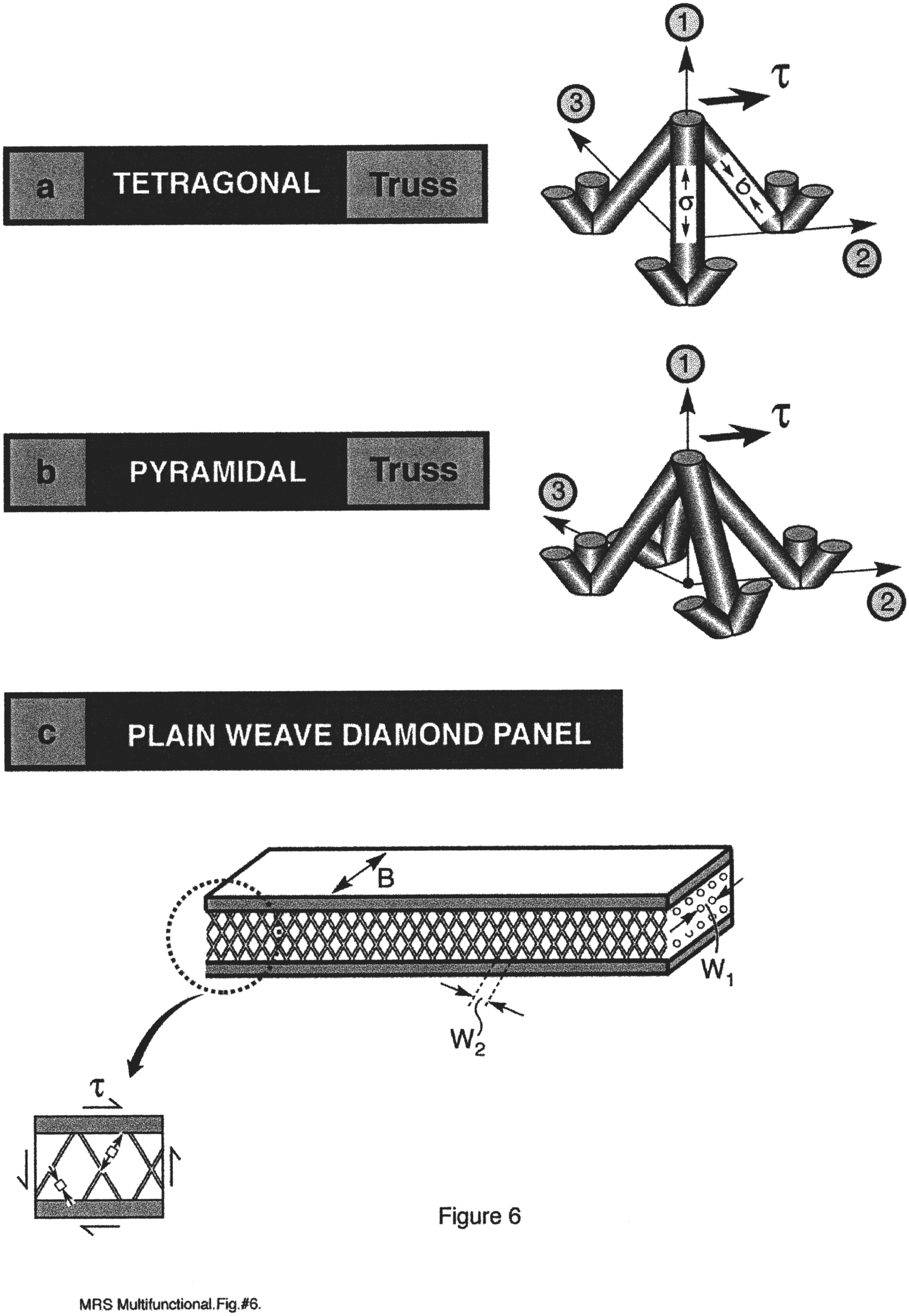
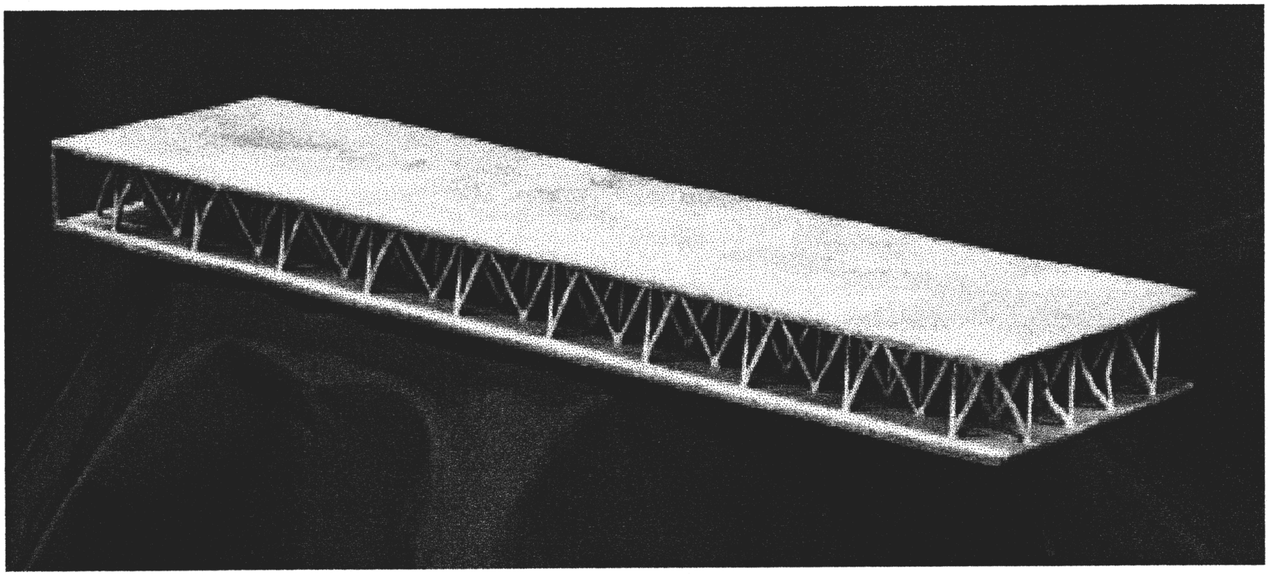


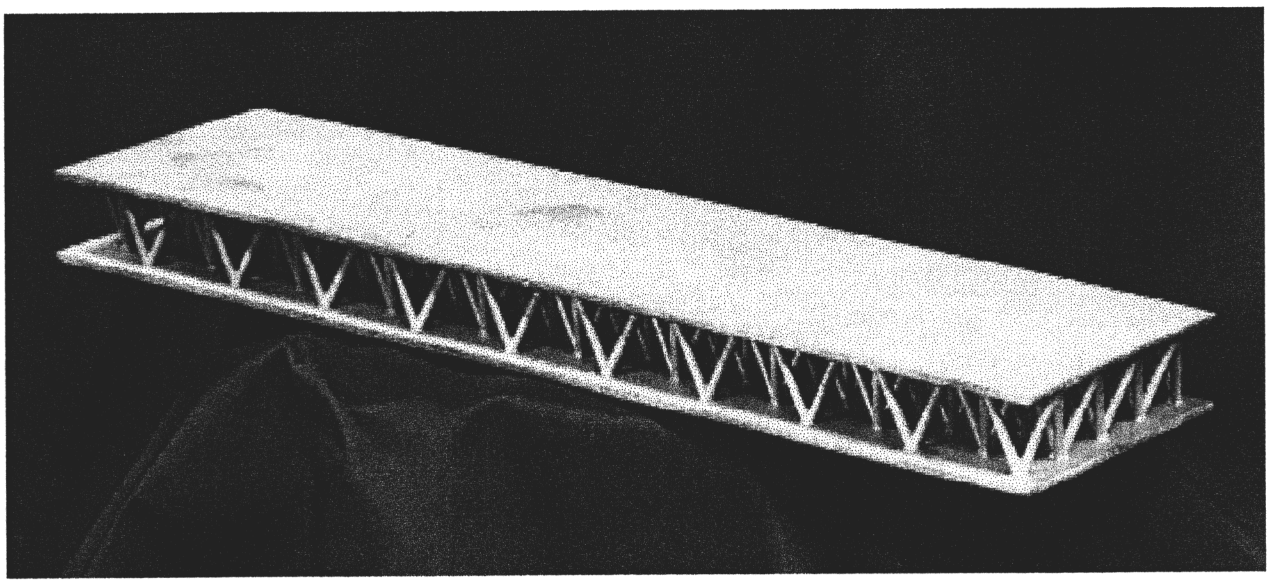
Figure 6

MRS Multifunctional.Fig.#6.

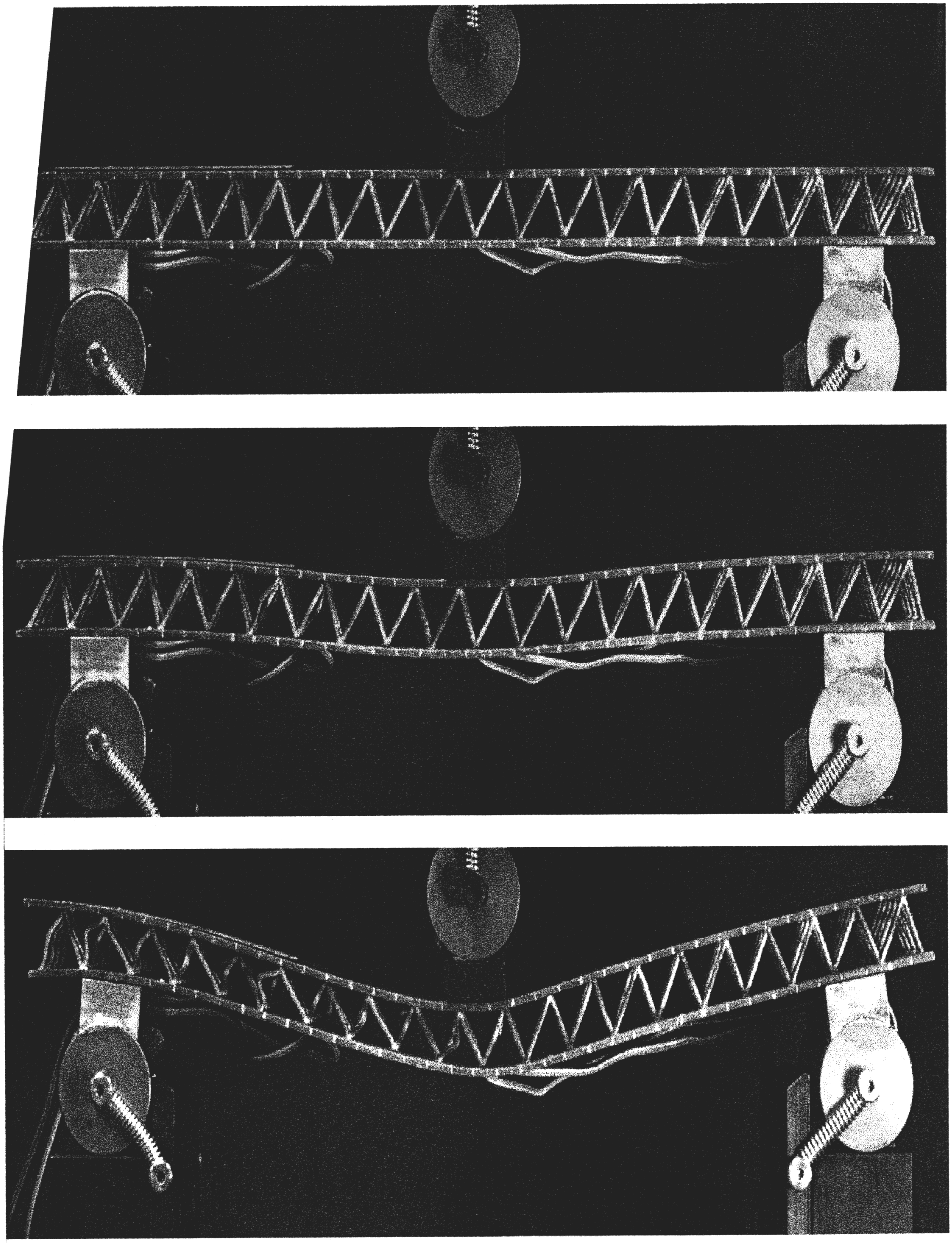
Be-Cu Investment Castings (Cu-2.0 wt% Be)



(a) Strut diameter = 1.25 mm (optimum design)



(b) Strut diameter = 2 mm (sub-optimal design)



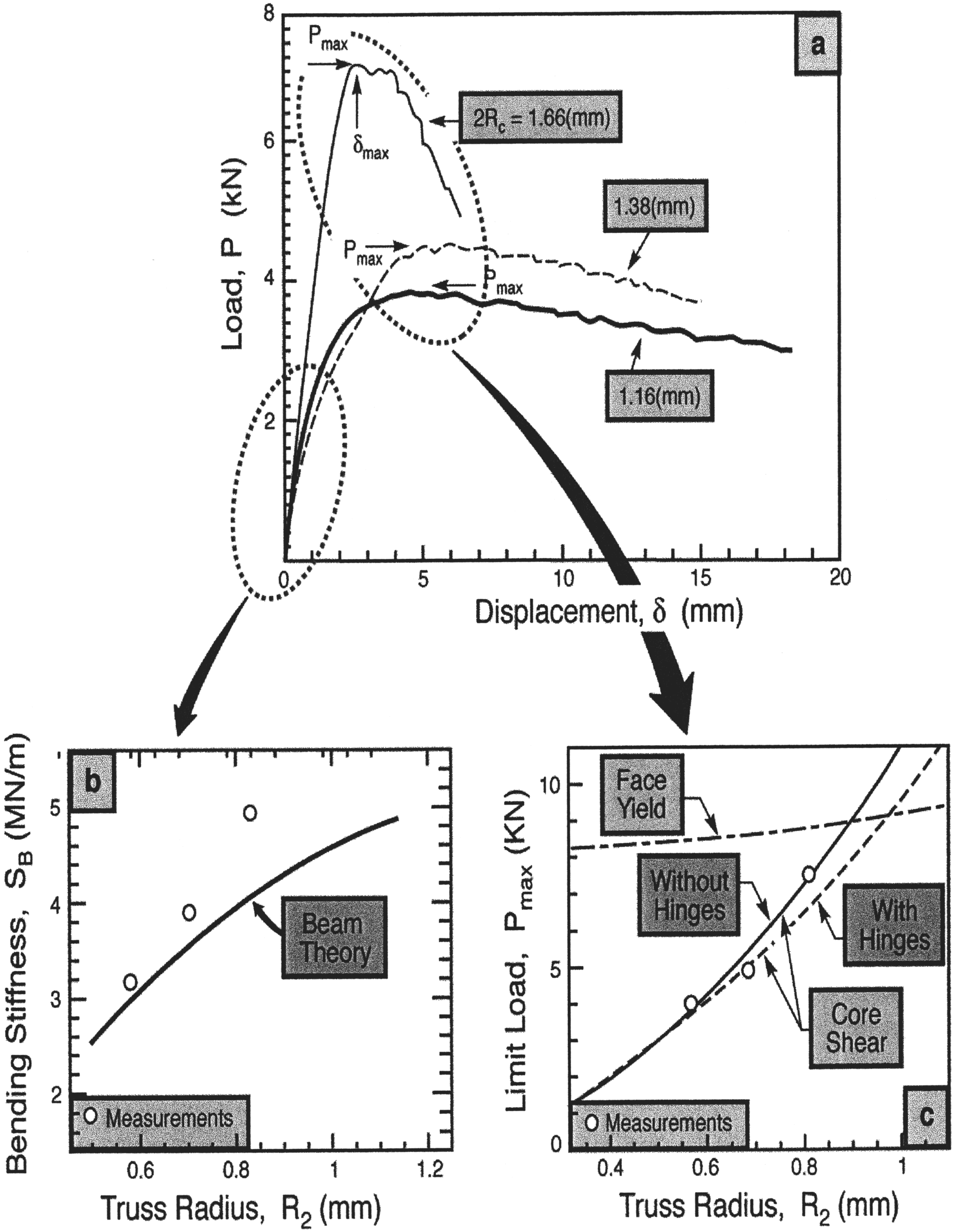

a
Load, P (kN)
Displacement, δ (mm)
P max
δ max
2Rc = 1.66(mm)
1.38(mm)
1.16(mm)
b
Bending Stiffness, S B (MN/m)
Beam Theory
Measurements
Truss Radius, R2 (mm)
Limit Load, P max (KN)
Face Yield
Without Hinges
With Hinges
Core Shear
Measurements
c
Truss Radius, R2 (mm)

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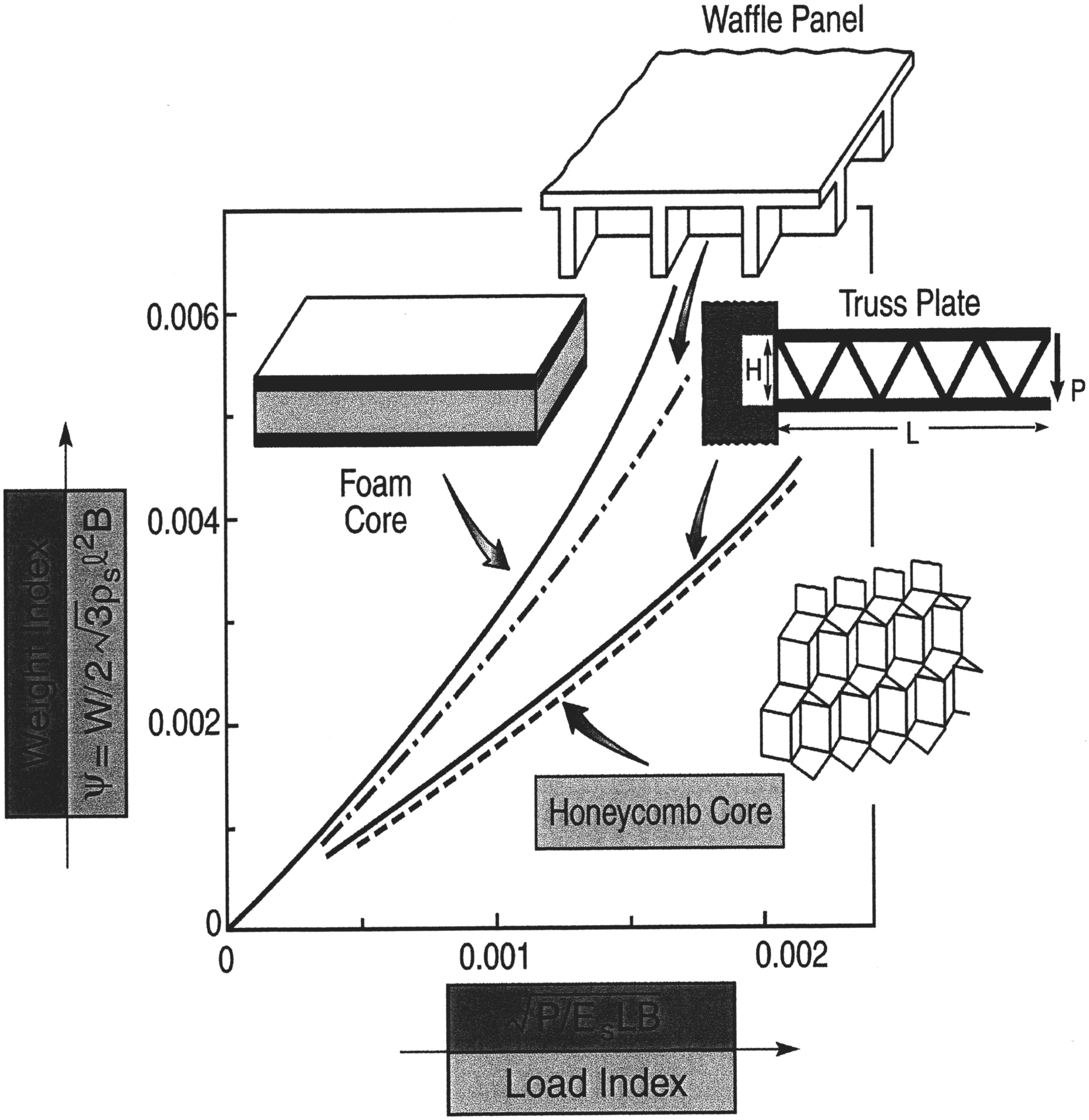
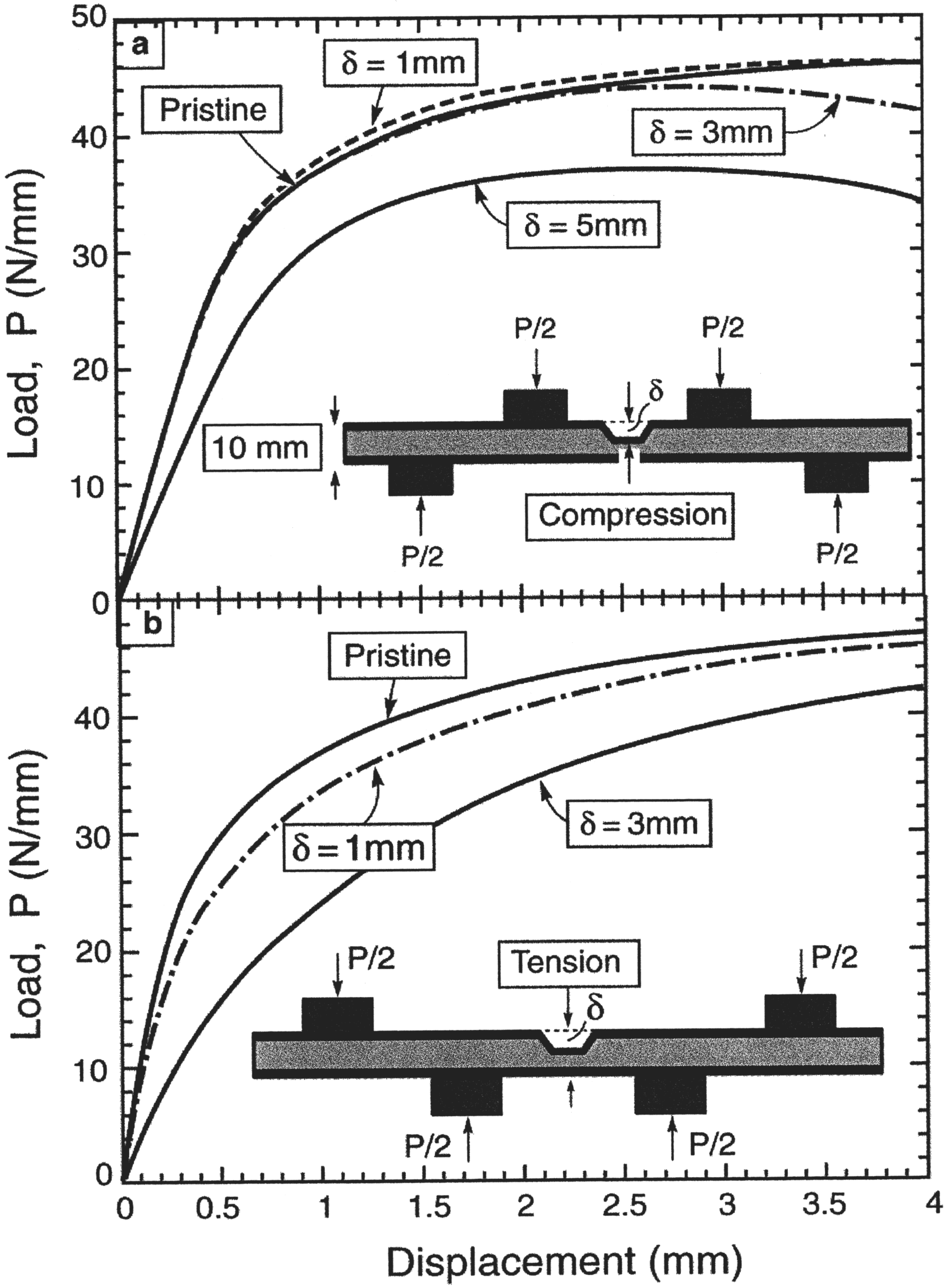
PLATE BENDING COMPARISON



ROBUSTNESS



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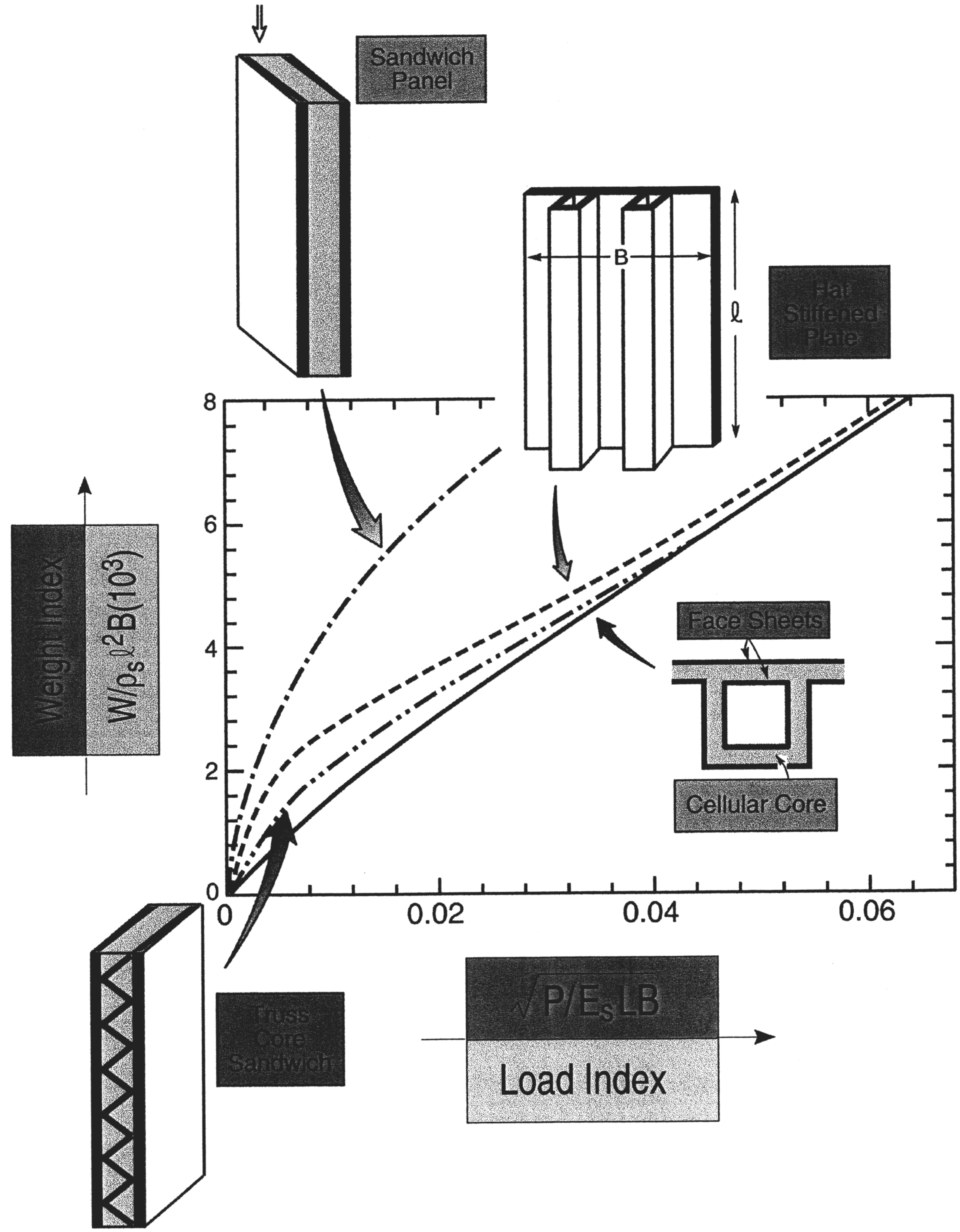
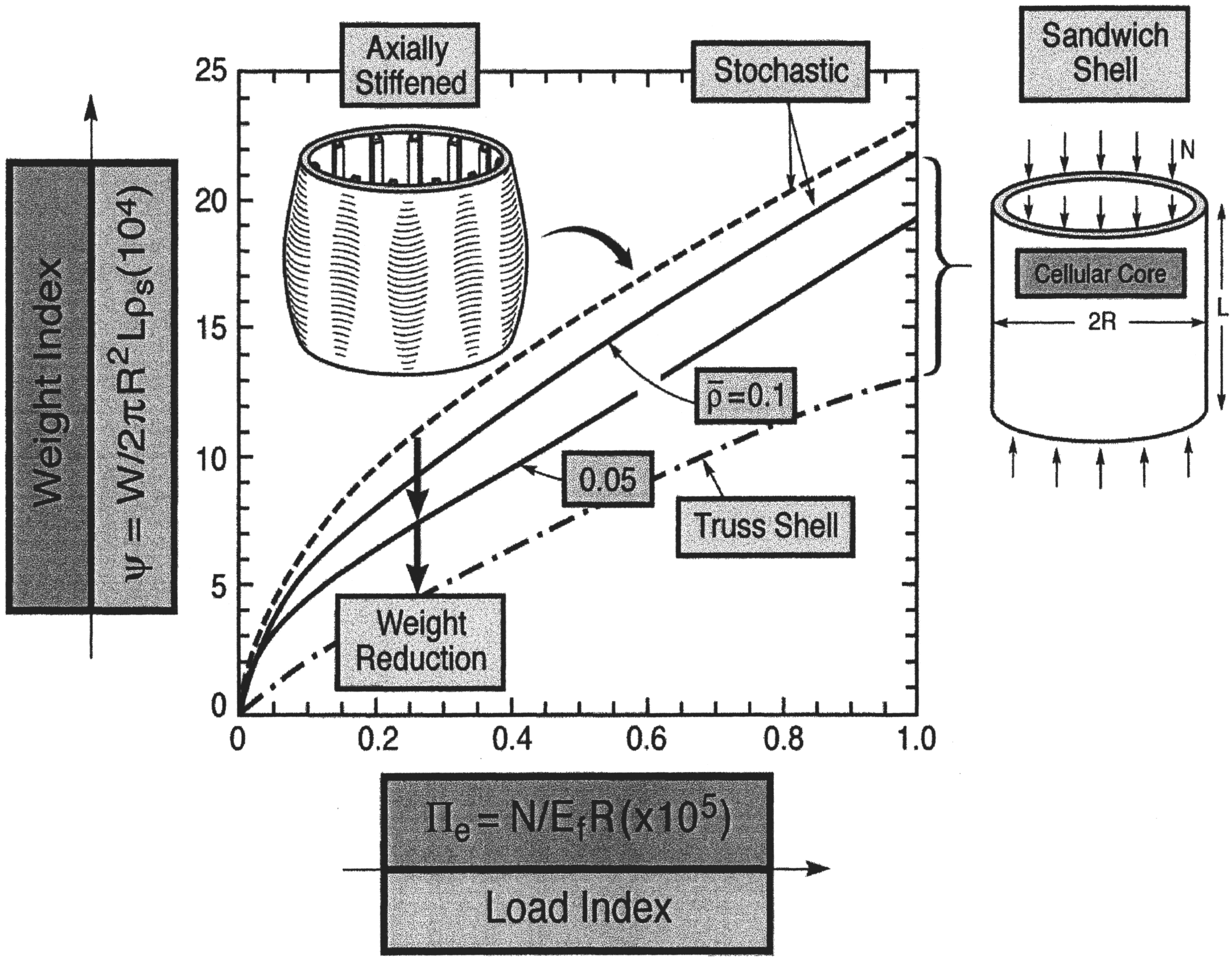
FLAT PANELS



Sandwich Panel
B
ℓ
Flat Stiffened Plate
Weight Index
$W/\rho_s \ell^2 B (10^3)$
8
6
4
2
0
0
0.02
0.04
0.06
Face Sheets
Cellular Core
Truss Core Sandwich
$\sqrt{P/E_s LB}$
Load Index

CURVED PANELS

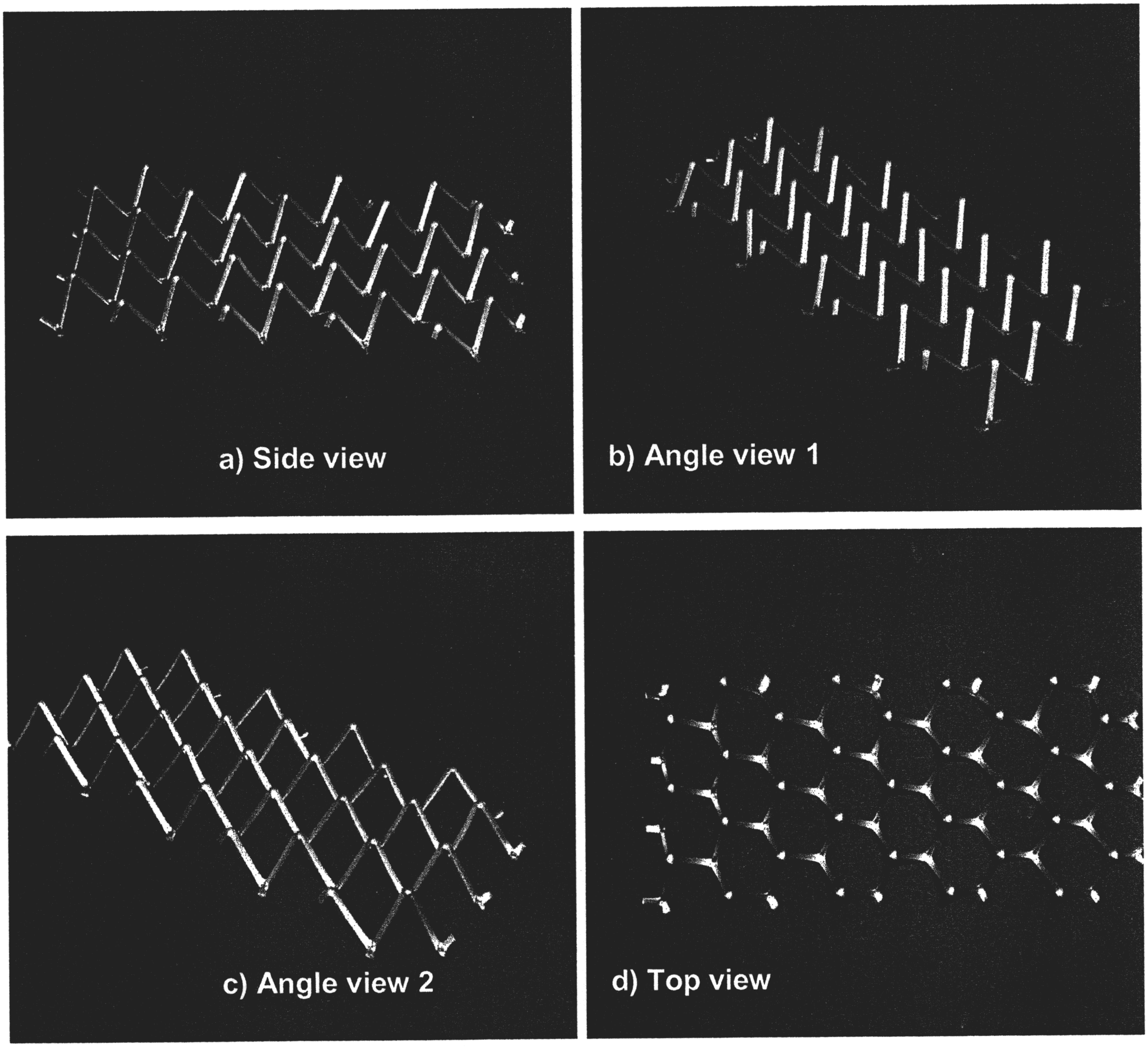


COST/PERFORMANCE TRADE-OFF

- Inferior Performance of Stochastic Relative to Periodic
- Lower Cost of Stochastic Relative to Periodic

Resolve Paradox Using Novel Fabrication Technologies

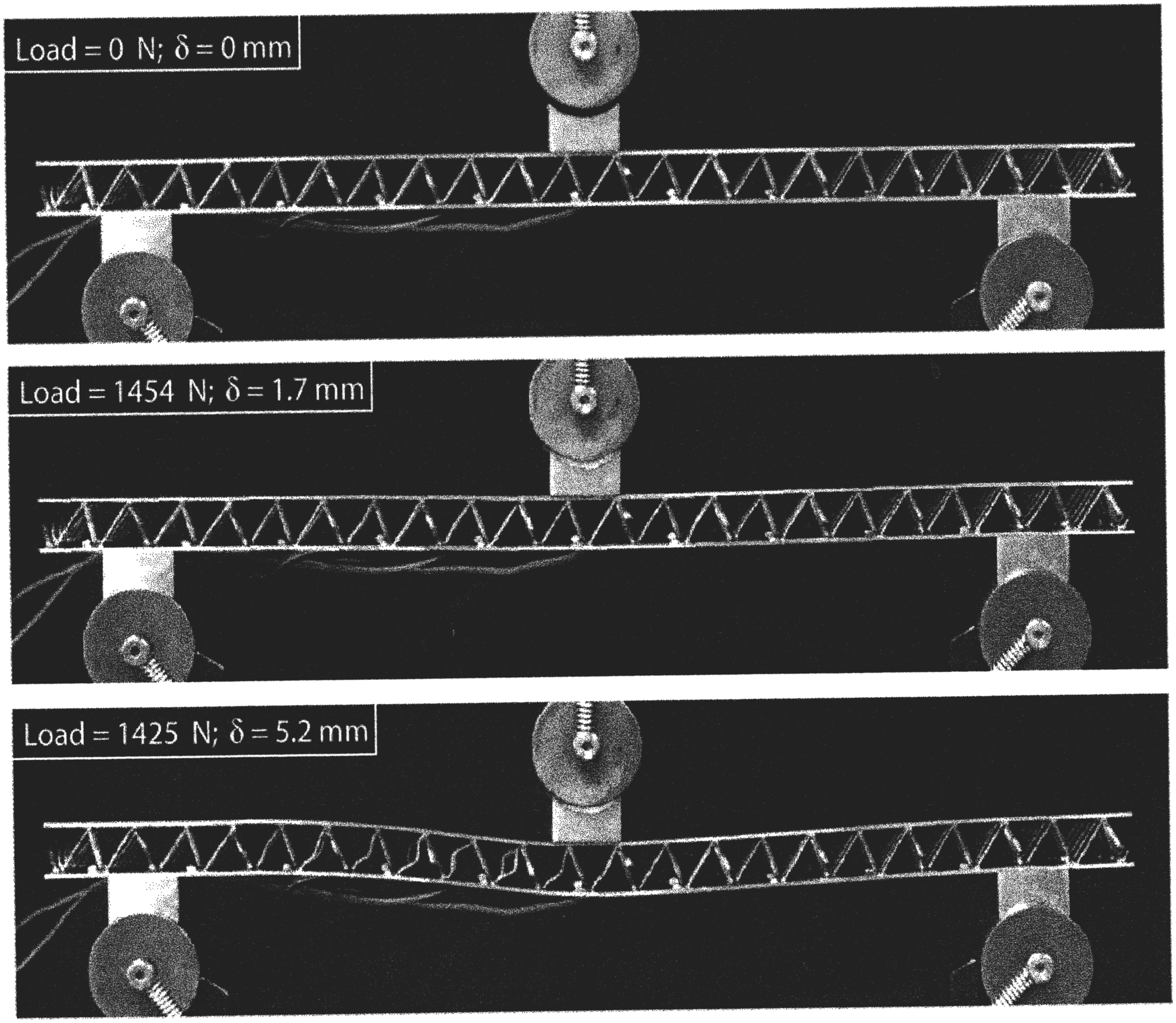
Wrought Stainless Steel Tetrahedral Truss



Material: 304 stainless steel
Tetrahedron height: ~9 mm
Relative density: ~1.6%

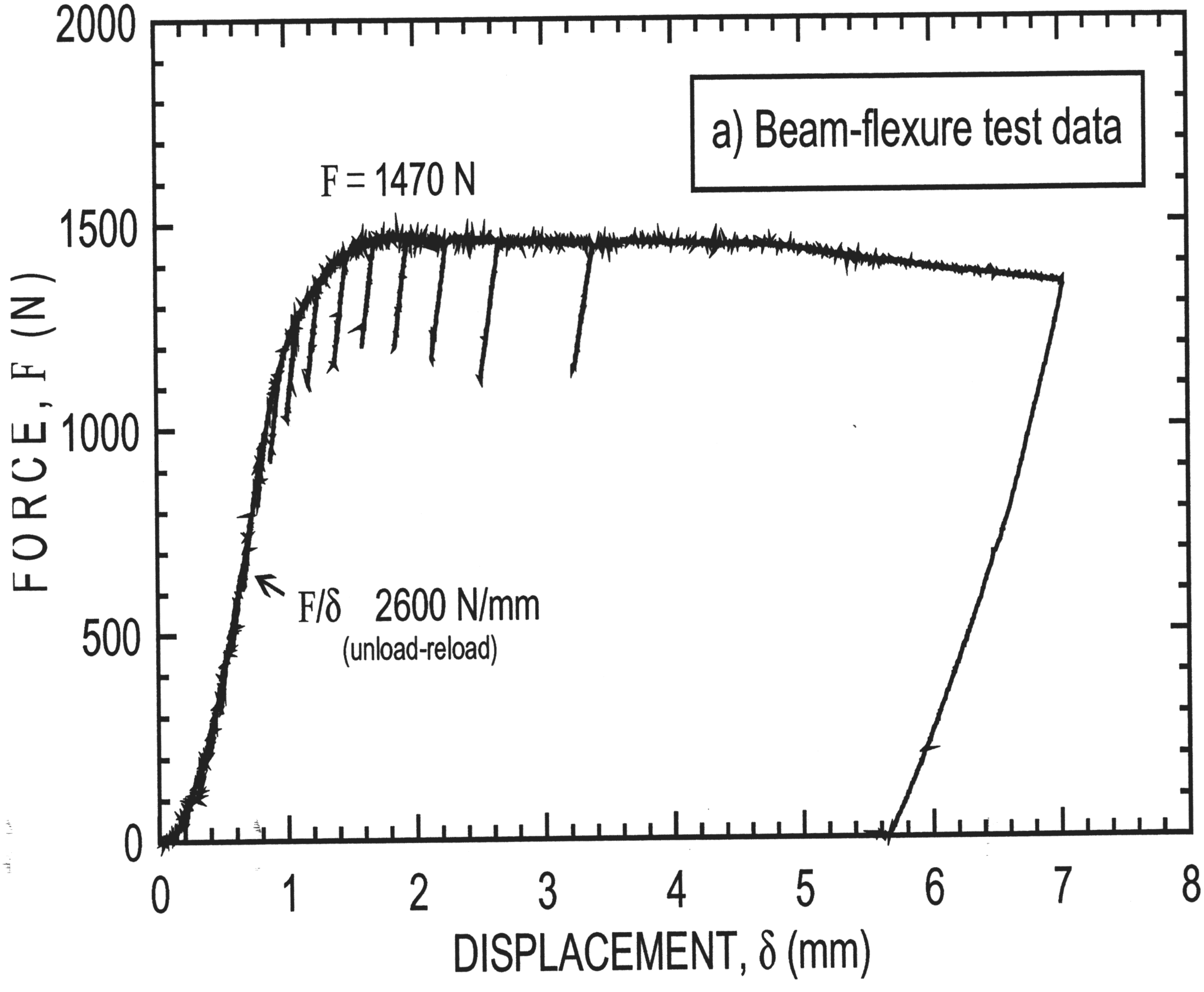
Truss width: ~1.25 mm
Truss thickness: ~0.57 mm

Al alloys (6061, 5951, 3003, 1100) Ti alloys, Cu, Ni alloys


Load = 0 N; δ = 0 mm
Load = 1454 N; δ = 1.7 mm
Load = 1425 N; δ = 5.2 mm

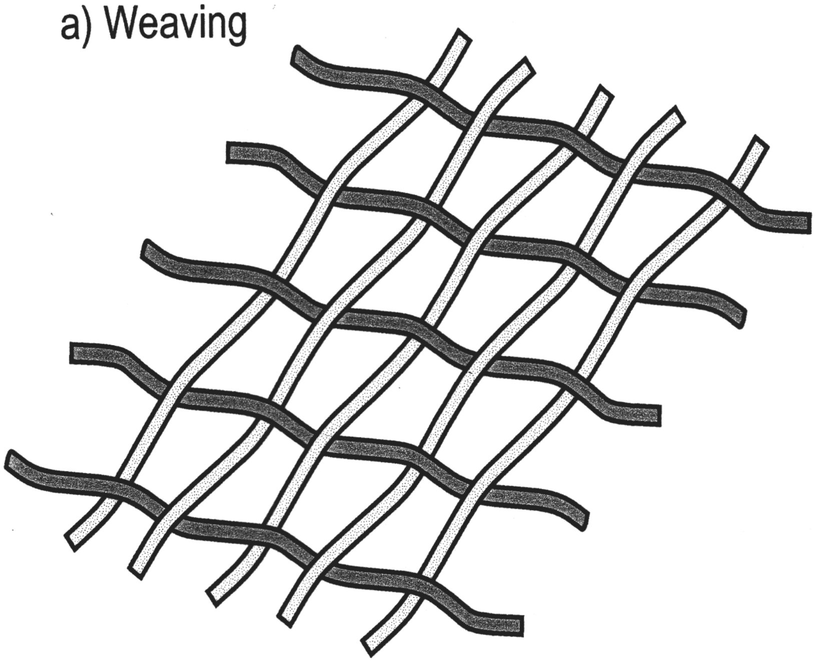
Constructed Cellular Solid Load Response:

3-Point Bending

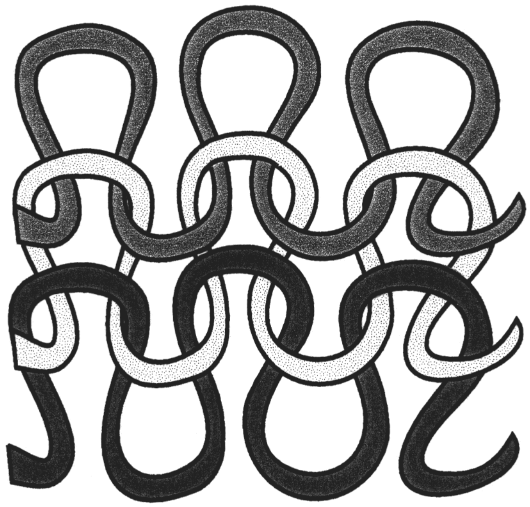


WEAVING TECHNOLOGIES

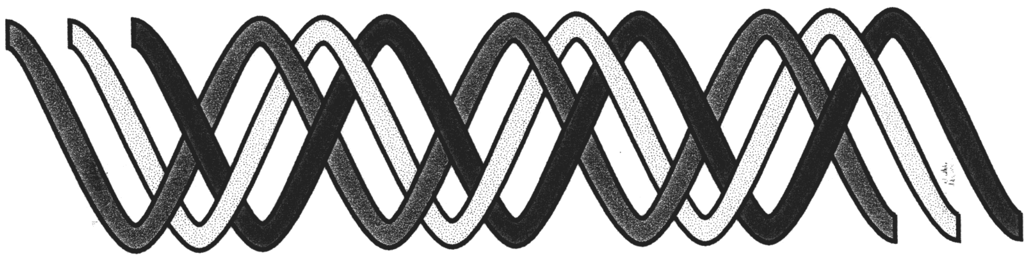
a) Weaving



b) Knitting



c) Braiding



PLAIN SQUARE WOVEN METAL CLOTH

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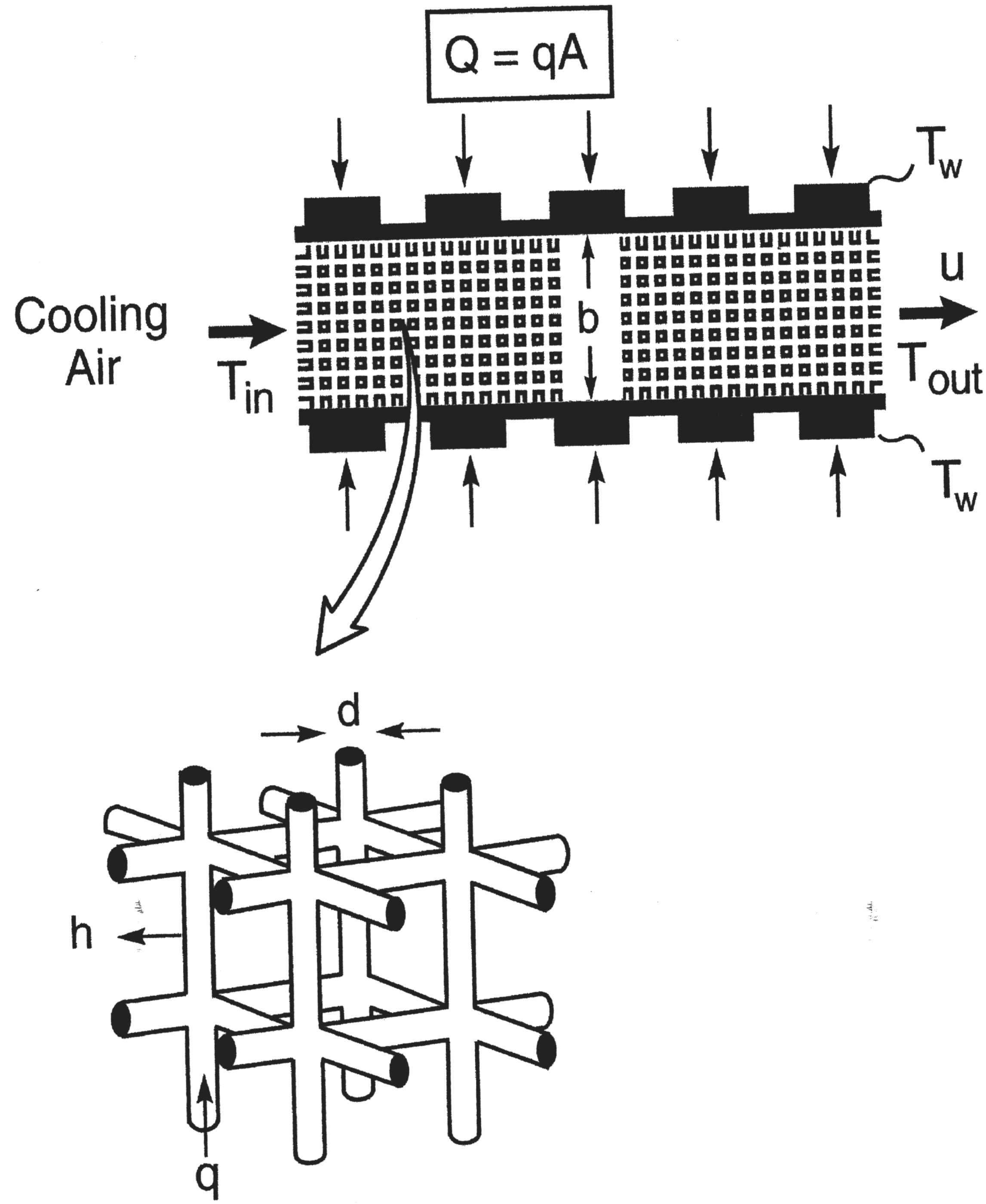
USE TOPOLOGY AS NEW VARIABLE

Plus Microstructure

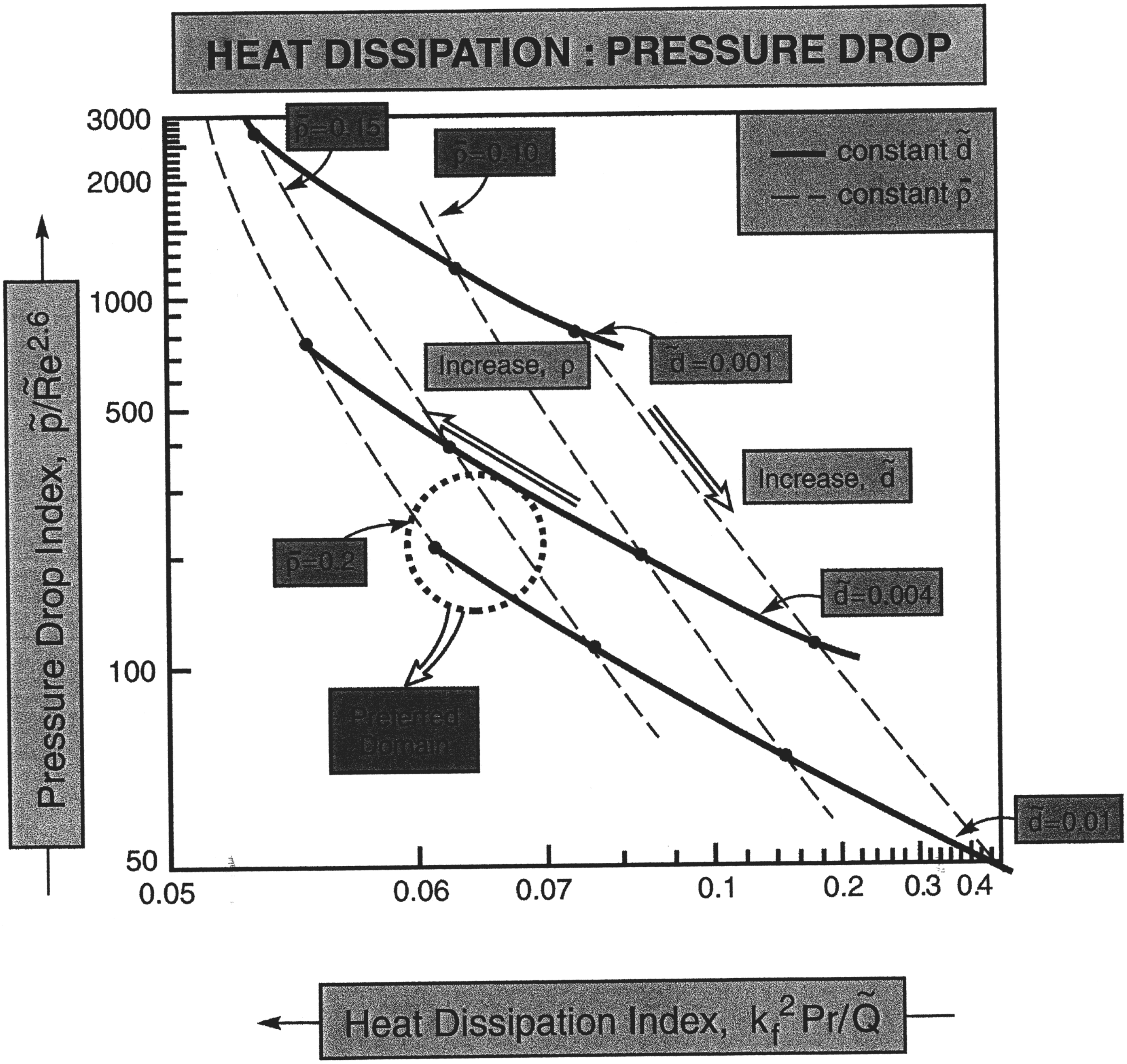
USE OPEN SPACE TO ACCOMMODATE NEW FUNCTIONALITIES

Heat Transfer

CELLULAR HEAT TRANSFER MEDIUM



CELLULAR HEAT TRANSFER MEDIUM



APPENDIX C

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14. ABSTRACT

This document is a proceedings of presentations and discussions conducted at Focus Group meeting on Materials and Structures for the DARPA Quiet Supersonic Platform (QSP) program, which took place at the Institute for Defense Analyses in June 2001. Attendees from aircraft companies, universities, and Government laboratories discussed possible new materials and structures fabrication approaches applicable to lightweight aircraft capable of supersonic flight, as defined by the Goals of the QSP program.

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